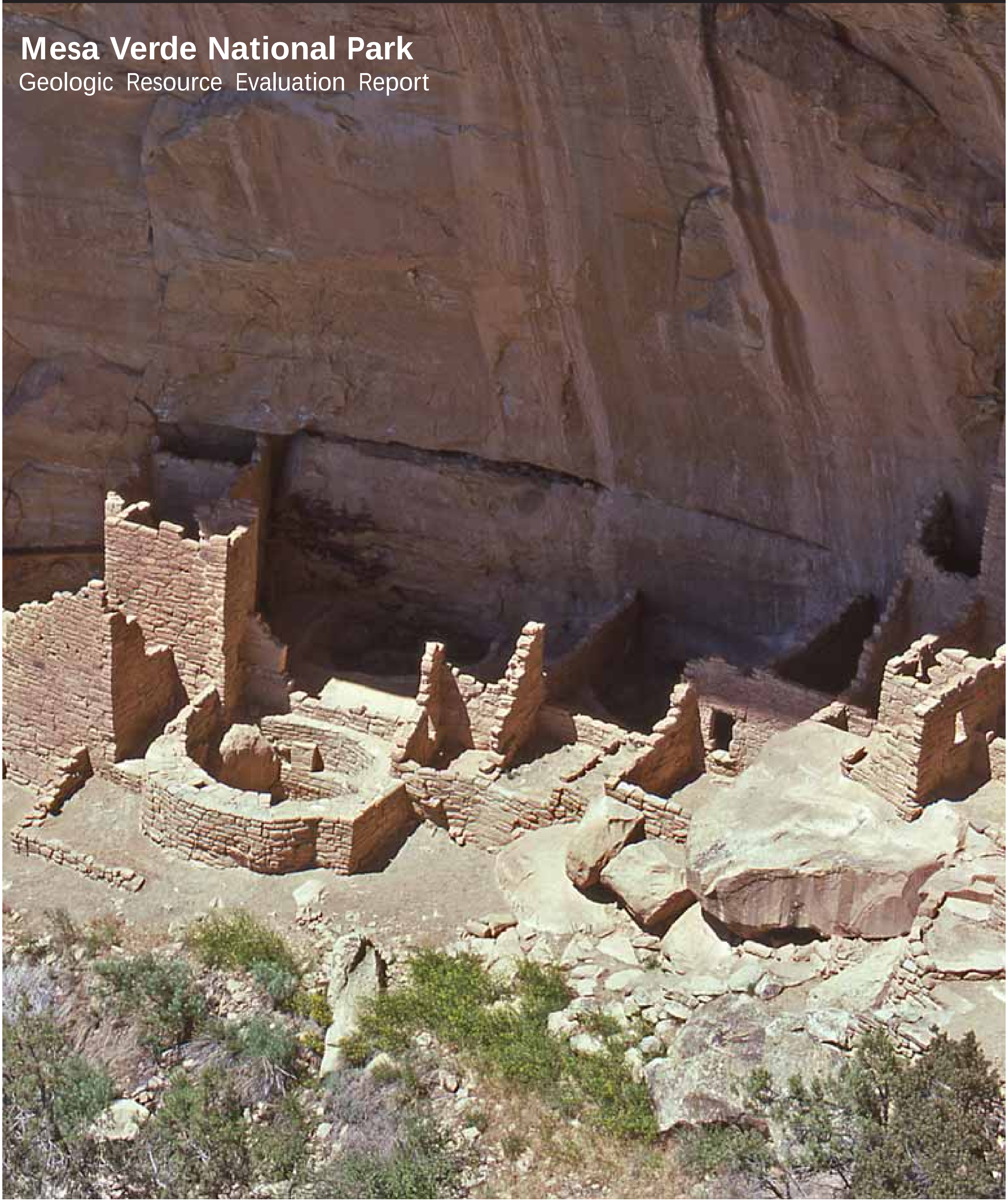
National Park Service
U.S. Department of the Interior

Geologic Resources Division
Denver, Colorado

Mesa Verde National Park

Geologic Resource Evaluation Report



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Executive Summary

This report has been developed to accompany the digital geologic map produced by Geologic Resource Evaluation staff for Mesa Verde National Park. It contains information relevant to resource management and scientific research.

Mesa Verde National Park (MEVE) encompasses roughly 81 square miles (52,073 acres) of the 520 square mile Mesa Verde, a deeply dissected mesa on the Colorado Plateau of southwestern Colorado. Mesa Verde is an area of broad, flat- topped mesas and narrow, north- south trending, steep- sided canyons. Mesa Verde NP was created in 1906 to preserve the archaeological treasures left by the Ancestral Pueblo people. The National Park Service (NPS) Geologic Resource Evaluation (GRE) Program has developed a digital geologic map, a geologic resources bibliography (GRBIB), and this Geologic Resources Evaluation report to assist park staff with understanding and managing Mesa Verde National Park's geologic resources.

In GRE scoping meeting held at the park in July of 1998, participants identified the following geologic issues:

- Rockfalls
- Slumps and landslides
- Flood erosion and deposition
- Groundwater flow and alcove development
- Debris flows

Rockfalls are probably the number one hazard to the park especially along roads and trails as well as in disturbed areas such as septic systems, utilities, and building sites. Little has been done other than monitoring and cleanup. Major slumps and landslides have affected park roads but little research has been done. Since the park has only one major road, a slump can prevent the ingress and egress of visitors. Flash floods and the resulting erosion and deposition have increased due to major fires that burn off the vegetation. Groundwater has seeped into some alcoves causing archeological damage and roof collapse. Springs are often the sites of alcove development. More study of the groundwater flow regimes is needed. In the past, debris flows have not been major hazard. However, with the encroachment of outside development near and down-flow from the park, this could become an important issue.

Other geologic issues that impact the park, but more local in extent are:

- Coal seam outcrop fires
- Rock jointing
- Mineral resources
- Interpretation

Coal seams occur mainly in the Menefee Formation of the Mesaverde Group. Outcropping coal seams can ignite by lightening and by surface fires. Joint systems in the rocks affect groundwater flow and could be planes of slippage, especially in areas of high groundwater flow or surface usage. The park is closed to mineral entry. However, there may be outstanding private mineral rights. And mineral development outside the park boundaries could greatly impact the viewshed, air quality, and noise level in the park.

Mesa Verde NP could improve geologic interpretation by having available for sale such items as fire histories, detailed geologic maps, and geologic road logs to visitors at the existing park museum and visitors center. Road signs for geologic unit names and unique features could further aid geologic interpretation.

The alcoves in which the Ancestral Puebloans built their cliff dwellings are some of the distinct geologic features at Mesa Verde National Park. Other geologic features can be seen from overlooks in the park. Distinct surface features on the mesa and in the alcoves have formed from recent mechanical and chemical weathering processes. Igneous dikes in the park are remnants of volcanic activity that occurred between 35 and 26 million years ago.

Surface exposures in Mesa Verde National Park are primarily Cretaceous- age strata. Each rock unit contains properties that influence their topographic expression, erosion potential, hazard potential, and global significance. Some units also contain potential paleontologic, cultural, or mineral resources.

The geology of Mesa Verde National Park lends itself to many possible scientific research projects. Some of these projects include:

- Stratigraphic sequence analysis
- Stratotype locations
- Cretaceous fossil
- Groundwater hydrogeology
- Mapping coal outcrops
- Soil and surficial geology mapping
- Fire recurrence studies and charcoal dating
- Quaternary studies, especially debris flows.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resources Evaluation Program.

Purpose of the Geologic Resources Evaluation Program

Geologic features and processes serve as the foundation of park ecosystems and yield important information for use in park decision making. The National Park Service (NPS) Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. The geologic component is carried out by the Geologic Resource Evaluation (GRE) Program administered by the NPS Geologic Resource Division.

The goal of the GRE Program is to provide each of the identified 270 "Natural Area" parks with a digital geologic map, a geologic evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and each is designed to be user friendly to non- geoscientists. In preparing products, the GRE team works closely with park staff and partners (e.g. USGS, state geologic surveys, and academics).

The GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss the geologic issues in the park. Park staff are afforded the opportunity to meet with the experts on the geology of their park. Scoping meetings are usually held in each park individually, although, to expedite the process some scoping meetings are multi- park meetings that address an entire Vital Signs Monitoring Network.

For additional information regarding the content of this report, please refer to the Geologic Resources of the National Park Service, located in Denver Colorado with up- to- date contact information at the following website: http://www2.nature.nps.gov/geology.

Park History

The Ancestral Puebloans (formerly known as the Anasazi) first entered the mesa around A.D. 600 (Nobel, 1991). Ancestral Puebloan sites are not distributed uniformly over the plateau. Geologic features dictated the location of Ancestral Puebloan communities. As farmers, the Ancestral Puebloans settled in areas where they found reliable seeps and springs, fertile soil, and a moderate climate. On the mesa, this meant that most communities were located at about 7,000 feet in elevation. Adjusting to the demanding climate and harsh terrain, they built a system of check dams and even small reservoirs to harness runoff from the intermittent streams. The Ancestral Puebloans carved farming terraces primarily on slopes with northeastern exposures to benefit from maximum soil moisture and reduced evaporation (Erdman et al., 1969).

Around A.D. 1200, many of the Ancestral Puebloans moved off the mesas and into cliff dwellings on Mesa Verde. By the mid- 1200s, about half the population of Chapin Mesa was living in these cliff dwellings. Beginning in A.D. 1276, a 23- year drought struck the region. Springs began to dry up. By A.D. 1300, Mesa Verde lay deserted (Noble, 1991). The early Spanish explorers of the 18th Century gave this area the name Mesa Verde, which is Spanish for "green table."

The first known geological reference to Mesa Verde comes in 1859 from the report of Professor John Strong Newberry of Columbia University. In 1874, William Henry Jackson, a photographer for the Geological and Geographical Survey of the Territories led by Dr. Ferdinand Vandeveer Hayden, and his guide, John Moss, found and named Two- Story Cliff House (Stegner, 1954). They may have been the first white men to enter a cliff dwelling. Jackson was the first to photograph both Mesa Verde and Yellowstone (in 1872).

Geologic Setting

The Mesa Verde area, in the southwestern corner of Colorado, includes about 520 square miles of deeply dissected tableland on the Colorado Plateau. Mesa Verde National Park comprises 81 square miles (52,073 acres) of this tableland and was created in 1906 to preserve the archaeological treasures left by the Ancestral Puebloan people (figure 1)

The Colorado Plateau Physiographic Province covers parts of Colorado, Utah, Arizona, and New Mexico (figure 2). The Colorado Plateau is a region of high plateaus and broad, rounded uplands separated by vast rangelands. The Mesozoic- age overthrust belt marks the west- northwest edge of the Colorado Plateau. The extensional, normal- faulted Basin- and- Range Province borders the Colorado Plateau to the west and south. The Rocky Mountains are to the east and the Rio Grande Rift forms the southeast border.

The Colorado Plateau is known for its laterally extensive monoclines that formed during the Late Cretaceous and Early Tertiary Laramide Orogeny. The basins adjacent to the steep limbs of the monoclines have been filled with sediment eroded from these folds. The steeply dipping eastern limb of the Hogback Monocline forms the west- northwest flank of the San Juan Basin located in northwest New Mexico. Mesa Verde lies on the gently dipping northwest limb of the Hogback Monocline (Condon, 1991; Wanek, 1959). The mesa is part of a wide, shallow syncline that plunges or tilts to the south. The sedimentary rocks at Mesa Verde are nearly flat lying but dip away from the structural high of the La Plata Mountains with gentle dips between 2- 3 degrees to the south (Wanek, 1959).

Very few faults have been mapped in Mesa Verde National Park relative to the surrounding area. Along the north rim, a normal fault trends east- west and can be traced across several promontories below Park Point (Wanek, 1959). The northern structural block has dropped down about 15 m (50 ft) relative to the southern block. Along the northwest rim, several small normal faults trend southeastward and coalesce. Displacement on the faults is about 30 m (100 ft). Farther south, a small normal fault cuts the western rim of the mesa. The fault trends east- west, and displacement is only about 12 m (40 ft) (Wanek, 1959). Most faults in Mesa Verde appear to be associated with gravity sliding near the edges of the escarpment. Joints that vertically fracture the Mancos Shale and Mesa Verde Group are common on the mesa.

The massive cliffs at Mesa Verde are composed of erosion resistant sandstones. Sandstone also forms the surface bedrock of the mesa. The slopes beneath the cliffs are less resistant to erosion and are composed of siltstone, mudstone, or shale.

The sandstones and shales at Mesa Verde rise abruptly to nearly 607 m (2,000 ft) above the surrounding plain (figure 1). The mesa of Mesa Verde slopes gently southward until it is truncated by the southwest flowing Mancos River, a tributary of the San Juan River (Wanek, 1959; Condon, 1991). Over a distance of about 18 km (11 mi), the elevation in the park changes from about 2,612 m (8,571 ft) above sea level at Point Lookout to roughly 2070 m (6,800 ft) on Chapin Mesa near the southern edge of the park. Such a change in elevation results in a topographic slope to the south of about 28 to 29 m per kilometer (145 to 150 ft per mile).

The sandstone that forms the bedrock surface at Mesa Verde is relatively porous and permeable so that water can flow through the sandstone. Melting snow and rain soak into the sandstone and percolate downward. Conversely, the shale beneath the sandstone is not very permeable so water does not travel through it very well. Instead, the groundwater flows along the contact of the sandstone and shale and emerges as springs or seeps along the canyon walls. The alcoves in which the Ancestral Puebloans built their cliff dwellings are the result of these seeps and of continued seasonal freezing and thawing that loosen the cement holding the sand grains together.

The La Plata Mountains lie to the northeast and the Sleeping Ute Mountain to the west of Mesa Verde National Park. On a clear day, the La Plata and Rico mountains to the northeast, the Sleeping Ute Mountain near Cortez, Colorado, the Carrizo Mountains in northeastern Arizona, the Henry Mountains and La Sal Mountains in Utah, and the lone spire of Shiprock are all visible from the mesa's rim. Except for Shiprock, which is the remnant of a central volcanic chamber, these mountain ranges are the result of igneous intrusions that formed mushroom- shaped laccoliths in the Early to Middle Tertiary Period. These intrusions pushed up the sediments without reaching the surface. Over time, erosion has exposed the inner igneous core of the ranges.

Igneous dikes mapped in Mesa Verde National Park have a similar orientation to some of the dikes radiating from Shiprock and are the same type of rock (Wanek, 1959). The dikes at Mesa Verde National Park, however, are somewhat of an enigma. Usually, as at Shiprock, volcanic dikes are more resistant to erosion than the surrounding sedimentary rocks and thus form obvious ridges in the landscape. In Mesa Verde National Park, a low mound or ridge is visible where a dike has cut through the soft Menefee Formation. However, the trace of the dike through the more resistant Cliff House Sandstone appears as a sharp- sided slot cut into the wall of the canyon and as a gully rather than a ridge across the surface of the mesa top.

During Pleistocene glaciation (1.6 Ma to 10,000 years ago), when large ice sheets covered much of North America, alpine glaciers scoured the mountains into peaks, knife- edge ridges, and shallow mountain lakes. Glaciers put the finishing touches on the higher peaks, transforming the San Juan Mountains, for example, from a rolling mountainous upland to an alpine wonderland of jagged peaks and mountain lakes.

Locally on the Colorado Plateau, glaciers formed at elevations below 1,828 m (6,000 ft) (Dr. Jim Johnson, Mesa State College, retired, personal communication, 2001). For example, the maximum extent of glaciation on the Grand Mesa near Grand Junction, Colorado, reached 1,650 m (5,400 ft). In the White River area, where Canyon Creek enters the Colorado River, glaciers reached an elevation of 1,768 m (5,800 ft). In the West Fork of the Mancos River area, east of Mesa Verde, glaciers flowing from the La Plata Mountains reached an elevation of at least 2,620 m (8,600 ft) above sea level, but the maximum extent is questionable (Dr. Jim Johnson, personal communication, 2001). Streams rushing from the toes of the glaciers carried voluminous amounts of debris down the canyons and out onto the plains.

The Colorado Plateau has been uplifted about 3,660 m (12,000 ft) since the end of the Cretaceous about 66 million years ago (Fillmore, 2000). Some of this uplift occurred rapidly geologically. As the rate of uplift increased, so did the rate of erosion. The Colorado River, for example, carved its present course within the last 6 million years. With uplift, streams throughout the Colorado Plateau began to dissect the landscape, forming the topography that is present today.

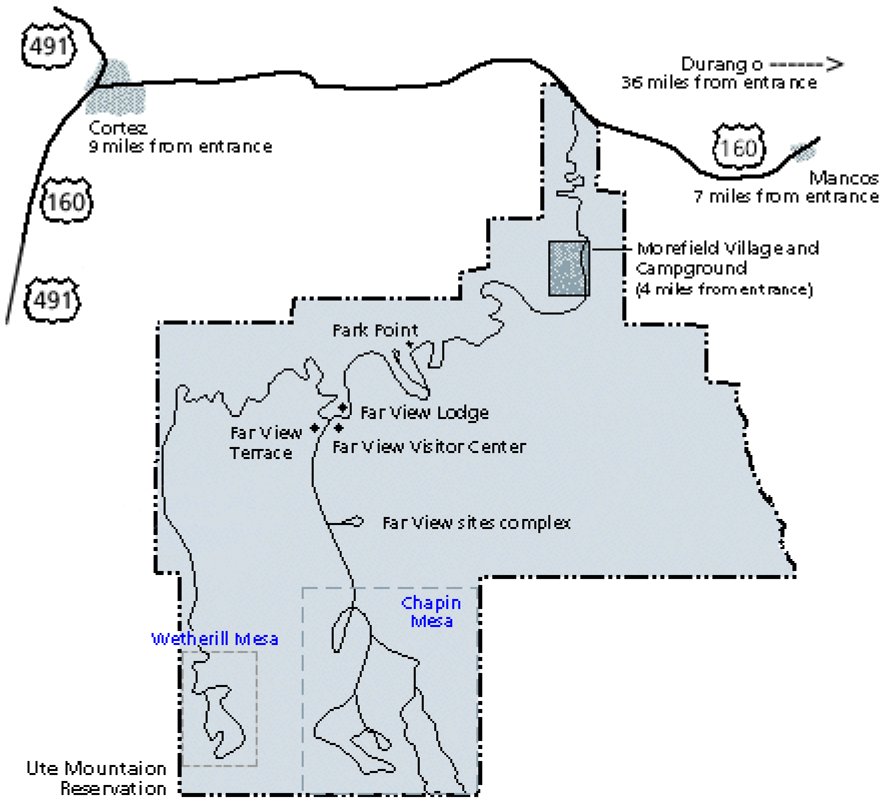

Figure 1. Location map of Mesa Verde National Park.

Geologic Issues

A Geologic Resource Evaluation scoping session was held for Mesa Verde National Park, July 14- 15, 1998, to discuss geologic resources, to address the status of geologic mapping, and to assess resource management issues and needs. The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

Most of the following geologic issues that have the potential to generate geological hazards were discussed at the 1998 workshop held in Mesa Verde National Park (Appendix B). Because of the unique geology of Mesa Verde, they remain issues today (Gregson, 1998).

Geological Hazards

Rock Falls: Because of erosion and freeze and thaw weathering processes on the sandstone cliffs, rock fall is the number one hazard to the public in Mesa Verde, especially along roads and trails. Aside from ongoing road monitoring and cleanup, little can be done to prevent the natural process of erosion. However, land use policies can help mitigate potential problems. For example, rock fall potential should be evaluated prior to siting new buildings, septic systems, utilities, roads, and trails. Forest fires in recent years have magnified rock fall hazards in the burned areas and proactive scaling has been done to help mitigate the most serious risks (George San Miguel, Mesa Verde NP, written communication, 2003).

Major Slumps and Landslides: The Mancos and Menefee Formations contain several beds of bentonite. Bentonite is an altered volcanic ash largely composed of the clay mineral montmorillonite, which has a crystal structure that absorbs water and swells when wet and shrinks upon drying. This swelling and shrinking leads to unstable slopes, slope failure, and constant road repair. The Park has repaired several slump- prone areas and engineered them to limit the local water infiltration rate and/or to drain and reduce pore- pressure in the affected sediment. Nonetheless, new areas of concern appear each year. The Park has only one major road, and that road crosses the bentonite- rich Mancos and Menefee shales.

Coal Seam Fires: In 2002, park staff located a smoldering surface coal seam in Morefield Canyon. This fire, known as the Horse Trap coal seam fire, was likely ignited by a wildfire in the park. The NPS Geologic Resources Division, Mesa Verde National Park, and the Colorado Division of Mines and Geology coordinated mitigation of this small fire. In May of 2005 the fire was extinguished using a fire excavation technique that involved removal of the burning coal materials, on- site cooling of these materials, and backfill against the excavated cut. Funding for this mitigation was secured by the Colorado Division of Mines and Geology. With numerous other coal seams spread across the park and many recent wildfires, there could be other burning seams in the park. Once ignited, coal seam fires are notoriously difficult to extinguish although, in the case of the Horse Trap coal seam fire, mitigation was successful.

Flooding and Debris Flows: Fires in the Mesa Verde area have increased erosion even beyond that anticipated in 1998. Increased runoff from burned areas contributes to amplified flooding, including some impressive canyon-bottom flashfloods. Mesa Verde is a highland with canyons cut by ephemeral streams. Short- duration, high- intensity rainfall events in semi- arid climates often lead to debris flows that effect lands adjacent to the canyons. With increased development outside park boundaries as well as increased runoff from fire- prone areas, an understanding of the hydrology of the mesa and a delineation of floodplains and mapping of debris flow deposits will be helpful in predicting future flooding and land use planning. Post- fire erosion on the East Escarpment has led to heavy sedimentation, which is harmful to the native fish species of the Mancos River within the park (George San Miguel, Mesa Verde NP, written communication, 2003).

Groundwater Flow

Water seeping into alcoves has caused some archeological damage and back (roof) collapse. Some of the seepage was traced to the drainage of domestic water and septic system leaching and has been subsequently mitigated. Still, understanding local groundwater flow, recharge areas, and infiltration and conductivity rates is important regarding any additional construction. The locations of springs and seeps also should be defined since they have archeological significance.

Joint Systems

An understanding of the joint systems in the Cliff House, Menefee, and Point Lookout sandstones is important with regard to potential faulting. Activities increasing the amount of water in joint systems may increase that potential for movement along joint planes.

Mineral Resources

Federal mineral leasing is prohibited in Mesa Verde National Park as is the location of new mining claims. Approximately 230 acres in the park are non- federally owned and could potentially be the subject of proposals to develop private mineral rights. If that occurred, the NPS would regulate that activity. However, no mineral production on this acreage is taking place at this time.

Coal: Surface coal mining is prohibited in the park. However, coal mining has occurred in the Mesa Verde area, adjacent to the park, in both the Dakota Formation and the Menefee Formation. In the past, Dakota coal was mined for local consumption. No adjacent coal mining issues have surfaced in the recent past.

Oil and Gas: At least two plugged and abandoned wells exist in the park; however, there are no active oil and gas operations in the park at this time. The Bureau of Land Management has conducted oil and gas lease sales on BLM property directly west of the park entrance road, several leases were sold in early 2000. No exploration or production has taken place on these leases to date. Limited oil and gas activity is also taking place north of the park entrance station, on the north side of Highway 160.

Intense coalbed methane production is occurring in the San Juan Basin, and more particularly, the Southern Ute Indian Reservation south of the park. Although this development is not immediately adjacent to the park boundary, impacts to park air resources are of concern. A large scale carbon dioxide extraction and distribution facility is located several miles west of the park; however this operation is not visible from park roads or overlooks.

Uranium: When southwest Colorado was explored for uranium deposits in 1976, no deposits were found in the Mesa Verde area (Haynes et al., 1972).

Adjacent Development

Approximately one half mile west of the park entrance station, the owner of a private in- holding, surrounded by Bureau of Land Management (BLM) land, has proposed subdividing the property for home construction. The BLM has undertaken an environmental assessment to analyze providing the private property owner with access across BLM lands to the proposed subdivision (personal communication George San Miguel, Mesa Verde NP, 2006). National Park Service concerns over this proposed development include: impacts to the park viewshed, decreased wildlife habitat, and the potential for expedition of future mineral development activities adjacent to park lands.

Potential Geologic Research Projects

Some potential research projects are listed below:

Unconformity-bounded Stratigraphic Sequences: Several transgressions and regressions of the Cretaceous shoreline are recorded in the Mesa Verde Group, which includes the Cliff House, Menefee, and Point Lookout formations. Sandstone packages and regional unconformities mark major reorganizations in these depositional regimes. Yet, a detailed stratigraphic analysis of the rocks bounded by these unconformities has yet to be published for the Cliff House Formation, Menefee Formation, and Point Lookout Formation at Mesa Verde National Park. Excellent exposures exist in the park, and data are available from the San Juan Basin to help correlate these formations. A study of the rocks in the Mesa Verde Group would help define the regional Cretaceous paleogeography, sedimentation rates, and possible past responses to tectonic pulses.

Type Locations: The excellent exposures of the Mesa Verde Group lend themselves as type localities for the Cliff House, Menefee, and Point Lookout Formations. The Cliff House Formation was named for the cliff dwellings in the park and a geological type locality is fitting. The Point Lookout Formation was named for the promontory that greets visitors coming into the park. The Menefee Formation also was named for exposures on the mesa. However, the type localities for these formations are vague and ill defined. The previously ill-defined type locality for the Mancos Formation is now located in the park (Kirkland et. al., 1995). Vertical stratigraphic sections of the other formations should be measured in detail and proposed as type localities.

Cretaceous Fossil Record: Extensive work on the Cretaceous fossil record, especially plants, is needed to enhance correlation and dating of the rocks, especially the Menefee Formation. A comparative collection and terminology for Cretaceous fossils is also needed.

Igneous Dikes: Numerous igneous dikes cut the Cretaceous sedimentary rocks of Mesa Verde. A study of their aerial extent and petrography would greatly enhance the understanding of their origin and emplacement.

Joint Patterns: Numerous joint sets fracture all the formations exposed on the mesa. Although similar, their orientations among the different formations are not well understood. A study of the joint patterns could help with land use planning and could be integrated with other joint studies on the Colorado Plateau.

Mapping Coal Outcrops (written comments from George San Miguel, Mesa Verde NP, 2003): Mapping coal outcrops would help pinpoint locations of current and future coal seam fires.

Groundwater Hydrology: A study of the local groundwater systems, recharge areas, and infiltration and conductivity rates will aid land use planning and protection of archeological sites. A map showing the locations of all springs and seeps should be a part of this study.

Soil Survey: Because soil fertility plays a significant role in the story of the Ancestral Pueblo people, soils from the new NRCS soil survey map could be correlated with the Ancestral Puebloan culture.

Fire Recurrence Studies: Participants at the 1998 workshop discussed radiometric dating of charcoal in sediments, similar to the study at Colorado National Monument, as a method to determine dates of fire recurrence on the mesa. Recent fires and changes in runoff make this project useful for evaluating fire recurrence, erosion potential, and debris flow history in the park.

Quaternary Studies: Several potential Quaternary studies were noted at the 1998 workshop and include:

- Paleosols that contain information on previous climate conditions
- A map identifying potential and current locations of rockfalls, debris flows, landslides, slumps, colluvial, and alluvial deposits could be important for land use planning
- A detailed surficial geology map needed to provide insight for both modern land use as well as ancient land use related to the cultural resources.

Interpretive Needs

Several interpretive needs were outlined at the 1998 workshop (Gregson, 1998). These included:

- A fire history of Mesa Verde National Park.
- A detailed geologic map.
- A geologic road log for the park.
- Replacement exhibits and signs destroyed by fire.
- New road signs identifying geologic unit names and unique features.

Road logs, road guides and new signs would provide information for park visitors. The road signs could be companions to a more detailed guidebook that would explain the features to the visitor. Don Baars has written a general book on the Colorado Plateau (Baars, 2000), but his book is not specifically targeted to the park.

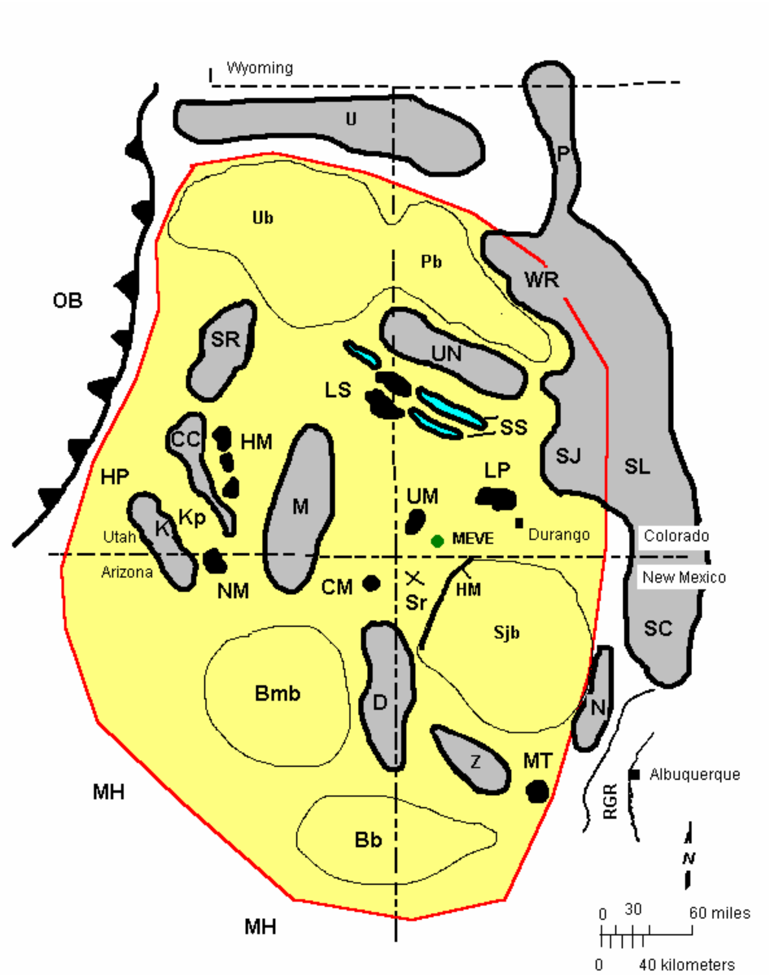

Figure 2. Location of Mesa Verde National Park in southwestern Colorado. The Colorado Plateau Province is outlined in red. MEVE: Mesa Verde National Park. Uplifts are shaded gray and include, from north to south: White River (WR), Uncompahgre (UN), La Sal Mountains (LS), San Rafael Swell (SR), High Plateau (HP), Circle Cliffs (CC), Henry Mountains (HM), Monument Uplift (M), Ute Mountains (UM), La Plata Mountains (LP), San Juan Mountains (SJ), Carrizo Mountain (CM), Navajo Mountain (NM), Kaibab Uplift (K), Defiance Uplift (D), Zuni Uplift (Z), and Mount Taylor (MT). Major basins on the Colorado Plateau include: Uinta basin (Ub), Piceance basin (Pb), Kaiparowits basin (Kp), San Juan basin (Sjb), Black Mesa basin (Bmb), and the Baca basin (Bb). South of the Uncompahgre Uplift are salt structures (SS) that trend northwest-southeast. Shiprock (Sr) is located in the northwest corner of New Mexico. The Hogback Monocline (HM) dips into the San Juan basin. The Overthrust Belt (OB) and the Mogollon Highland (MH) are two thrust-related features that border the plateau to the west and south, respectively. Solid triangles indicate the block of rocks that have been thrusted over underlying strata. Basement-cored uplifts of the Laramide Orogeny are found to the north and east in the Uinta Mountains (U), Park Range (P), San Luis Mountains (SL), Sangre de Cristo (SC), and Nacimiento Mountains (N). The Rio Grande Rift (RGR) borders the plateau to the southeast.

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Mesa Verde National Park.

Cuesta Features

Mesa Verde is a *cuesta*, a sloping plain terminated on one side by a steep slope. The mesa slopes gently to the south, but has a 2,000 –foot escarpment on the north side formed by an outcropping of Point Lookout sandstone. The mesa surface is only slightly less steep than the southward dip of the sedimentary beds (dip slope). At one time, Mesa Verde was connected with the La Plata and San Juan Mountains. Sloping from the mountains was a *pediment* surface, a broad bedrock erosional surface that typically develops at the base of a mountain front in arid regions. The Mesa Verde cuesta is a remnant of this pediment surface.

With uplift, the Mesa Verde region was divided into separate land forms by streams that incised into the pediment. When headward erosion by McElmo Creek tributaries intersected south- flowing streams with lower gradients than their own, they captured those streams and rerouted them to McElmo Creek, which flows west outside the park.

The cuesta is drained by the Mancos River, which has cut a deep, broad valley along eastern and southern edges of Mesa Verde. Headward erosion by intermittent streams dissected the mesa into 15 long, parallel, steep- sided canyons separated by narrow uplands. The canyons drain to the Mancos River.

Alcoves

Alcoves in the Cliff House Sandstone were used by the Ancestral Puebloans. Alcoves form where massive, cliff-forming sandstone overlies soft, erodible shale beds. When groundwater, percolating down through the porous and permeable Cliff House Sandstone, intersects less permeable shale layers, it is diverted along the contact of the sandstone and shale. When the groundwater reaches the canyon wall, the slightly acidic water dissolves the carbonate minerals that cement the sand grains together. The loosened grains are removed by seasonal freezing and thawing, wind, water, and gravity.

The canyons vary in depth. For example, the part of the canyon where Spruce Tree House cliff dwelling is located is less than 100 feet in depth compared to the 240 - foot deep canyon at the Cliff Palace dwellings. The larger alcoves have been cut into the upper part of the Cliff House Formation. The controlling factor of alcove formation is not the depth of the canyon, but the location of regional bentonite layers that impede vertical groundwater flow.

In some areas, at Long House for example, water comes in contact with bentonite. The swelling of the bentonite applies pressure on the overlying sandstone and helps promote the disintegration of the sandstone. This bentonite layer can be seen just above the floor of many of the deeper alcoves. Grain by grain, a niche forms in the rock wall; gradually the niches widen and connect to form alcoves.

Because the contact between the sandstone and shale is relatively horizontal, the floors of the alcoves are flat and almost level. This allowed the Ancestral Puebloans to have a stable platform upon which to build. In some of the alcoves, ripple marked sandstones are reminders of ancient shorelines. Water from seeps in the back of some of the alcoves collects in dissolution pits. The Ancestral Puebloans carved feeder grooves from these dissolution pits to the alcove proper.

Overlooks

The vistas are also special features at Mesa Verde National Park. At the Mancos Valley Overlook, which is close to the contact between the Mancos Shale and the Point Lookout Sandstone, the La Plata Mountains are visible on the horizon. The high flat erosion surface to the east that gradually rises to the mountain range is the remains of the ancient erosion surface of very early Tertiary time (Griffitts, 1990). Across Mancos Canyon, the level bench along the canyon wall is an old stream terrace that developed when the stream stopped cutting downward for a time. A volcanic plug can also be seen on the east canyon wall from this overlook.

At the Montezuma Valley Overlook, the sheer cliff to the north is known as the Knife Edge. The old road formerly looped around Knife Edge and back to Morefield Canyon until 1957. Constructed on the soft Mancos Shale, the road was difficult to maintain and was abandoned in 1957 when the tunnel was built to connect Prater and Morefield Canyons. To the west, the city of Cortez lies on a flat erosion plain underlain by Dakota Sandstone. The rich red soil on this plain is loess (wind-blown silt) that holds moisture well. Farther to the west is the Sleeping Ute Mountain, formed by the intrusion of a laccolith.

At Park Point, the La Plata Mountains, another laccolithic mountain range, can be seen to the east; the volcanic San Juan Mountains to the north; and the silhouette of Sleeping Ute Mountain to the west, so named because the mountain range resembles a man lying on his back with his head to the north and arms crossed over his chest. On a clear day, Shiprock is visible over 30 miles to the south. Mancos and Dakota deposits floor the broad flat plain below the Mesa Verde. Along the rim, small faults have dropped the Menefee coal beds about 50 feet down against the Point Lookout Sandstone. To the south, a good overall view shows the flat top of the mesa sloping gently to the south and cut by sharp shouldered canyons.

A complete sequence of the sedimentary rocks of Mesa Verde is visible from the North Rim Overlook. The trace of a fault scarp in the Point Lookout Sandstone can also be seen across the canyon. Several landslides are located on the north side of the canyon. The slides remove the vegetation from the steep slopes and thus encourage further rapid erosion.

Surface Features

MEVE also contains several distinct surface features. At Spruce Tree House, the surface of the rock is weathered into a polygonal pattern of grooves called “turtle backs.” Both mechanical and chemical factors may play a part in developing these features.

Concretions occur throughout the park. Some are like mud balls with a foreign object like a pebble or fossil shell in the center. Others are the result of minerals, calcium carbonate (lime) and/or iron oxide, precipitating in a part of a sandstone and cementing the sand grains together. Those parts of the sandstone that are more resistant to erosion frequently result in knobby features in the rock. Shapes of these concretions are variable, and some of the more unique ones were found by the Ancestral Puebloans.

Rain water has left distinct solution patterns and other marks on the surface of the park. Shallow depressions in sandstone collect runoff. Precipitation forms a very weak acid, which can dissolve the lime cement in the sandstone. The shallow depressions deepen in the center, and little grooves leading from the center begin to develop as rapid runoff filling the center begins to dissolve the cement in softer parts of the rock.

Desert varnish forms vertical dark streaks on the upper rim of the alcoves. The cause of desert varnish is not universally agreed upon but it seems to be a combination of several factors. Bacterial action, in the presence of moisture, fixes manganese and iron particles brought in with wind blown dust.

Volcanic Features

The San Juan Mountains, northeast of Mesa Verde, are the remnants of a great volcanic field that resulted from volcanic activity about 35 to 26 million years ago. Dikes at Shiprock, New Mexico, and several small igneous dikes in the park resulted from this volcanic activity. Usually, igneous dikes are more resistant to erosion than the sedimentary rocks they intrude and form obvious ridges on the landscape after the sedimentary rocks have eroded away. At Mesa Verde, however, differential weathering has left a different weathering pattern. Where the dikes cut through the soft Menefee Formation, a very low mound or ridge may be visible, but the trace of the dike in the more resistant Cliff House Sandstone is usually a sharp sided slot cut into the wall of a canyon (Griffitts, 1990).

Map Unit Properties

This section provides a description for and identifies many characteristics of the map units that appear on the digital geologic map of Mesa Verde National Park. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

In Mesa Verde National Park surface exposures consist primarily of Cretaceous- age Mancos Shale and Mesa Verde Group consisting of the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone (Map Unit Properties Table; Appendix A). Tertiary- age gravels overlie the Cliff House Sandstone and Tertiary volcanic dikes cut through the sedimentary strata. Fluvial terrace gravels and wind- blown sediment have been deposited during the Quaternary. Soils are currently developing on the present Holocene topography.

The following Map Unit Properties Table identifies properties specific to each unit present in the stratigraphic column including: the map symbol, unit name, description, topographic expression, erosion potential, hazard potential, potential paleontologic, cultural, and mineral resources, and global significance.

Map Unit Properties Table

Period	Unit Name (Symbol)	Description	Topographic Expression	Erosion Potential	Hazard Potential	Paleontologic Resources	Cultural and Mineral Resources
Quaternary	Alluvium deposits (Qal)	Sand, silt, & gravels deposited mainly in stream beds & flood plains; soil, sand, & gravel of alluvial origin; variable thickness	Associated with stream topography	Depends on grain size & process	Low	Holocene insect fossils from a number of Ancestral Puebloans archeological sites (Scott et al., 2001)	Sand & gravel
	Colluvium deposits (Qls)	Irregular, heterogeneous deposits of boulders, gravel, sand & silt derived mostly from talus & landslides; variable thickness	Hummocky landslide topography	Depends on depositional slope	Low		Sand & gravel
	High level terrace gravels (Qtg)	Alluvial gravel and boulder deposits on mesa tops in Mancos Valley. Qtgt: high- level terrace gravels with travertine cement.	Define old stream terraces	Low on mesa tops	Low		Sand & gravel
	Travertine (Pleistocene) (Qtr)	Calcium carbonate deposits, often associated with major joints & faults. Possibly the result of hot spring activity. Age uncertain (2003). No age- dating research on these deposits.	Variable	High	Low		
Tertiary	Minette (Oligocene: 32- 27 Ma) (Ti)	Igneous plugs & dikes, light gray to almost black biotite & olivine- rich lamprophyric rocks containing abundant breccias & locally rounded cobbles of basement rocks; variable thickness.	Dikes	Less resistant to erosion than sandstone	Low		
Unconformity							
Cretaceous	Mesaverde Group: Cliff House Sandstone (Kch)	White to red- brown, pale to dark yellowish- orange, fine to medium grained sandstones interbedded with sandy shales; upper & lower units of massive sandstones separated by a unit of thinner bedded sandy shales; cliffs are generally over 30 m (100 ft) thick; sandstone is cross- bedded; intertongues toward base with Menefee Fm. & includes locally an upper tongue, a middle tongue (Barker Dome tongue) & a lower tongue; 61 - 91 m (200- 300 ft.)	Cliff former; sandy shale unit is recessive beneath upper sandstone cliff	Sandstone is resistant to erosion; middle shale unit is less resistant	Potential cliff collapse if middle shale unit and Meneffee shale erode and cliffs are undercut	<u>Invertebrates</u>: Ammonites: *Baculites maclearni* Landes; fragments of *Placenticeras sp.*; Bivalves: *Ethmocardium whitei*, *Cymbophora*, *Modiolus*, *Dosinopsis*, *Inoceramus*; echinoids; sea star; <u>Vertebrates</u>: jaw, fins, teeth from bony fish *Enchodus*, shark teeth; amphibians, reptiles (mosasaurs, plesiosaurs, turtles). <u>Trace fossils</u>: burrows of Crustacean *Ophiomorpha*	Puebloan cliff dwellings in large alcoves; Puebloan sites on mesa top. Potential hydrocarbon reservoir rock in the subsurface
	Mesaverde Group: Menefee Formation (Kme)	Dark gray & brown carbonaceous shales, thin siltstones & thin coal beds in upper & lower units; middle sandy unit of poorly sorted, irregular bedded sandstones, sandy shales & bentonite beds; lower coal member about 28 m (93 ft) thick with individual coal beds ranging from 0.1- 0.4 m (0.4- 1.2 ft) thick; coal beds are lenticular and extend several miles across Mesa Verde area; middle member is 30 m (100 ft) thick in park. Coal seams in upper member range from 0.1- 0.5 m (0,3- 1.6 ft) thick. Lenticular sandstone is cross- bedded. Intertongues with Cliff House sandstone & Point Lookout Sandstone; total thickness: 104- 244 m (340- 800 ft)	Sandstones form benches & cliffs, shales form slopes; two sandstone units 6 m (20 ft) thick in middle member form ledges along East Rim.	Sandstone is resistant to erosion; shale is less resistant	Unknown	No invertebrate or vertebrate fossils. Fossil plants: petrified wood (conifer); *Auricaria*; palms *Sabal* & *Sabalites*; grass blades, crushed stem of *Calamites*; twig of *Sequoia*, unknown fern; monocot *Brachyphyllum*, leaves from *Sycamore, Theaceae, Laurel, Camelia, Ficus* trees; flower bud from *Paleoaster iniqueriende*	Thin coal seams
	Mesaverde Group: Point Lookout Sandstone (Kpl)	White to yellow to yellowish- orange, fine to medium grained sandstone with shaly sandstone breaks, highly cross- bedded; 88- 147 m (290- 480 ft). Upper member is massive, cross- bedded sandstone; massive sandstone is a series of overlapping sandstone wedges; individual beds range from 30 cm (1 ft) to over 100 cm (3 ft) thick; total thickness: 70- 104 m (230- 340). Lower member is alternating sandstone & shale; beds are 3 cm (1 in) to 30 cm (1 ft) thick and interlayered with dark olive- gray shale containing fossil debris; shale contains gypsum; total thickness: 25- 38 m (80- 125 ft).	Upper member is a cliff former: Lower unit forms ledges and slopes	Sandstone is resistant to erosion; shale is less resistant	Cliff/ledge collapse if shale erodes and sandstone is undercut	Few identifiable fossils; trace fossils are common; large *Baculites* cf *haresi*, broken inoceramids, drift wood	Small alcoves in the massive upper sandstone Potential hydrocarbon reservoir rock in the subsurface
	Mancos Shale: Cortez Member (Km)	Cortez Member: Dark gray to black; transitional from calcareous silty shale & marlstone at the base to interbedded sandstone and shale at the gradational upper contact with the Point Lookout Sandstone; primarily dolomitic mudstone with little bentonite; almost 396 m (1300 ft) thick	Slope former	High	Erosion may cause slope to fail	Invertebrates: baculites, scaphites, *Placenticeras planum* Hyatt, crinoid *Uintacrinus*	Mancos Shale is a potential hydrocarbon source rock in the subsurface

Period	Unit Name (symbol)	Description	Topographic Expression	Erosion Potential	Hazard Potential	Paleontologic Resources	Cultural and Mineral Resources
Cretaceous	Mancos Shale: Smokey Hill Member (Kms)	Smokey Hill Member: Dark gray to black, calcareous shale & marlstone; minor bentonite; located about 274 m (900 ft) above the base of the Mancos Shale; about 91 m (300 ft) thick; also referred to as the *Niobrara* member	Prominent oyster bench about 274 m (900 ft) above base of Mancos; forms prominent benches around north edge of the Mesa Verde	High except for oyster bench	Erosion may cause slope to fail	Oyster *Pseudoperna congesta*; *Scaphites depressus; Baculites codyensis*; Inoceramids *Inoceramus (Platyceramus) platinus, I. (Endocostea) balticus, I. (Magadiceramus) subquadratus*; ammonites *Desmoscaphites bassleri, Scaphites hippocrepis*	
	Mancos Shale: Montezuma Valley Member (Km)	Montezuma Valley Member: Dark gray, calcareous shale & marlstone; contains concretions; thin unit about 15 m (50 ft) thick.	Slope former	High	Bentonite may cause building & maintenance problems	Numerous prionocyclids, scaphites, baculites, bivalves, inoceramids, oysters	
	Mancos Shale: Juana Lopez Member (Kmj)	Dark, silty shale with numerous beds of orange weathering calcarenite & thin limestone; shales contain bentonite; highly fossiliferous; located about 150 m (500 ft) above base of Mancos Shale; 43 m (140 ft) thick; oldest member of Mancos to crop out within the park.	Limestone ridges separated by shale units;	Relatively resistant to erosion	Bentonite may cause building & maintenance problems	Highly fossiliferous; ammonites and bivalves are common & well preserved. Ammonites: *Prionocyclus macombi* Meek, *P. wyomingensis* Meek, *P. novimexicanus*, *P. Quadratus* Cobban; *Scaphites warreni, S. whitfieldi; Baculites undulates* d"Orbigny, *B. yokoyami*; Bivalves: *Inoceramus dimidius* White, *I. Perplexus* Whitfield, *Nacaisolopha lugubris*	
	Mancos Shale: Blue Hill Member (Km)	Dark gray, noncalcareous shale or mudstone with some interbedded sandstones; contains bentonite, but not as much as Fairport member; about 76 m (250 ft) thick; not exposed in MEVE; not easily recognized topographically	Slope former	High	Bentonite may cause building & maintenance problems	Sparsely fossiliferous	
	Mancos Shale: Fairport Member (Km)	Dark gray, very calcareous, bentonitic shale; about 28 m (92 ft) thick. Not exposed in MEVE.	Slope former	High	Bentonite may cause building & maintenance problems	Ammonites: juvenile Collignoniceras woollgari; also small oysters, fragments of inoceramids, barnacle fragments, shark teeth	
	Mancos Shale: Bridge Creek Member (Kmb)	Light gray limestone & calcareous shale about 24 m (80 ft) above Dakota- Mancos contact; 15 m (50 ft) thick; also referred to as the *Greenhorn* member; crops out north of MEVE capping small erosion remnants of soft Graneros Shale and is about 3- 4 m (10- 14 ft) thick.	Topographic limestone bench surrounded by recessive shale units	High except for limestone bench	Bentonite may cause building & maintenance problems	Varied molluscan fauna: inoceramids of genus *Mytiloides*; ammonites of genera *Mammites*, *Watinoceras, Baculites, Kamerunoceras*, and others; pyritized clams	Mancos Shale is a potential hydrocarbon source rock in the subsurface
	Mancos Shale: Graneros Member (Km)	Dark gray calcareous bentonitic shale about 24 m (79 ft) thick; not exposed in MEVE but found a short distance to the north. Total thickness of Mancos: 609- 700 (2000- 2300)	Slope former	High	Bentonite may cause building & maintenance problems	Lowest part has limited fauna; upper part is an almost solid bed of small oysters, *Pycnodonte newberryi*	
	Dakota Sandstone (Kd)	Dark brown, gray to yellowish- orange, medium to coarse grained sandstone; cross- bedding; contains shale lenses & coal beds; not exposed in MEVE; 30 +/- (100 +/-)				Specimens of *Tempskya* sp. were collected adjacent to the park	Coal

Geologic History

This section highlights the map units (i.e., rocks, and unconsolidated deposits) that occur in Mesa Verde National Park and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that created the landscape.

Mesozoic Era: Cretaceous Period

Lithospheric plate collision in the Cretaceous resulted in mountain building along the western margin of North America as the Sevier Orogeny formed a roughly north-south trending thrust belt that is well defined in present-day southern Nevada, central Utah, and western Montana (figure 3). As the mountains rose in the west, the Gulf of Mexico separating North and South America continued to rift open in the south, and marine water advanced northward into the expanding Western Interior Basin. Marine water also began to transgress from the Arctic region.

As the shoreline continued to advance into eastern Utah and western Colorado in the Lower Cretaceous (115- 135 Ma), a predominantly fluvial system changed to a coastal plain depositional system with coastal swamps, lagoons, and beach environments (Dakota Sandstone) (Condon, 1991; Morris et al., 2000). The inland sea advanced and retreated many times during the Cretaceous until the most extensive interior seaway ever recorded drowned much of western North America (figure 4). The Western Interior Seaway was an elongate basin that extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4827 km (3,000 mi) (Kauffman, 1977). During periods of maximum transgression, the width of the basin was 1600 km (1,000 mi) from western Utah to western Iowa. The western margin of the seaway coincided with the active Cretaceous Sevier orogenic belt so that sedimentation into the basin from the rising mountains was rapid. Rapid sedimentation led to further sediment loading and downwarping along the western margin.

Mancos Shale: Mancos Shale forms the lowermost sequence of rock units exposed within the park (Map Unit Properties Table; Appendix A). Except where the Mancos is capped by resistant Point Lookout Sandstone, the Mancos Shale forms flat eroded surfaces such as the plain surrounding the park. Where it is overlain by sandstone, the Mancos forms highly dissected, dark gray escarpments.

In 1959, Wanek measured 609 m (1,998. ft) of Mancos Shale from just north of the highway to the Point Lookout Formation, but he did not subdivide the Mancos into any smaller units (Wanek, 1959). Kirkland and others (1995) completed a transect along this same section in which they measured 700 m (2,297 ft) of Mancos Shale and subdivided the Formation into eight distinct members, from youngest to oldest:

- Cortez member
- Smoky Hill member
- Montezuma Valley member
- Juana Lopez member
- Blue Hill member
- Fairport member
- Bridge Creek member
- Graneros member

The oysters in the Graneros member indicate deposition in a shallow, low energy, quiet marine environment as transgression pushed the shoreline to the west of Mesa Verde. Wave action must have been minimal in order to preserve, intact, the small oysters and shark teeth.

Active magmatism along the western margin of North America provided great quantities of volcanic ash that settled to the ocean bottom during this time (Christiansen et al., 1994). The volcanic ash altered to bentonite, which is white on a fresh surface but weathers to a rusty orange color (Kirkland et al., 1995). Because it forms from volcanic ash, bentonite can be dated radiometrically providing an important time markers for correlating sedimentary rocks over large distances on the Colorado Plateau.

The overlying shales in the Fairport and Blue Hill members represent quiet deposition in a marine environment. The Fairport member is very calcareous and contains more bentonite beds than the Blue Hill member (Kirkland et al., 1995). Abundant, calcareous foraminifera fossils found in the Fairport member indicate a relative sea level rise. Sparse arenaceous foraminifera in the Blue Hill indicate a subsequent sea level fall (Aubrey, 1991).

The fine- to coarse- grained limestone of the Juana Lopez member was deposited during another sea level rise. The Juana Lopez member represents the second major transgressive pulse in the Mancos Shale and was deposited when sea level rise reached its maximum extent (figure 5). It is the oldest part of the Mancos Shale exposed within the park (Scott et al., 2001). Like the Bridge Creek, the Juana Lopez member forms limestone ridges separating the shale units. The Juana Lopez is one of the most laterally persistent Cretaceous units in the southern Rocky Mountain region (Aubrey, 1991). The Graneros is found a short distance to the north where small erosion remnants may be capped with Bridge Creek (Greenhorn) Limestone.

Following Juana Lopez deposition, sea level did not dramatically rise or fall but remained in a dynamic equilibrium as the depositional regime began to change again. The relatively thin, Montezuma Valley member above the Juana Lopez member was identified by Kirkland and others (1995) and named by Leckie and others (1997) but is difficult to physically correlate to the detailed measured section of Wanek (1959).

The boundary between this member and the overlying Smoky Hill member is an unconformable contact that may represent another lowstand of sea level in the Mancos Sea (Aubrey, 1991; Kirkland et al., 1995). The unconformity marks an abrupt decrease in the number of bentonite beds in the overall formation.

Except for the Cortez and Smoky Hill members, these units in the Mancos Shale contain bentonite which swells with the addition of water and shrinks upon drying, which may cause problems with trail, road and facility construction and maintenance.

Calcareous shale and marlstone, a rock containing both calcium carbonate (lime) and clay, of the Smoky Hill member may signify the third major transgression of the Mancos Sea (Aubrey, 1991). The Smoky Hill may be correlative to rocks mapped in the Southern Ute Indian Reservation to the southeast.

The Cortez member represents the beginning of a regressive stage of deposition and consists of shallow marine, near shore deposits (figure 6). The member becomes progressively sandier, contains dolomitic (Ca,Mg carbonate) mudstones, and is transitional with the overlying Point Lookout Formation. The yellow-gray sandy shales and shaly sandstones of this upper, transitional member contain ripple marks, and trails, tracks, and burrows of animals that lived in shallow marine environments. As the shoreline advanced into the Mesa Verde region, the clay and silt particles were winnowed from the sand and deposited farther offshore to the northeast. Gradually, the layers of Point Lookout sandstone became more prominent in the area than beds of shale and siltstone (figure 7).

In summary, for roughly 15 million years (from 80 to 95 Ma), clay, silt, sand, and shell debris were deposited in the Mancos Sea that covered Mesa Verde National Park (Molenaar, 1983). At first glance, the Mancos appears to be 700 m (2,300+ ft) of uniform, monotonous black and gray shales with a few scattered limestone beds. Yet, the history of the Mancos reflects at least four major changes in depositional systems where shoreline and near- shore environments were replaced by new environments created as sea level rose and fell. In addition, fossil evidence suggests that ocean currents within the Mancos Sea were not homogeneous. At times, the currents circulated oxygenated water throughout the water column allowing life to prosper at all levels, including within the muddy sea bottom. During marine transgressions, however, the circulation in the seaway was restricted to the upper water layer, and black, organic- rich mud accumulated in the oxygen- poor sea bottom. In those environments, the fossil material includes very few, if any, bottom fauna.

Late Cretaceous - Mesa Verde Group. The Mesa Verde Group consists of three formations: Point Lookout Sandstone (oldest formation), Menefee Formation, and Cliff House Sandstone (youngest). Between 297- 463 m (974 - 1519 ft) of rocks in the Mesa Verde Group have been measured in Mesa Verde National Park (Map Unit Properties Table) (Wanek, 1959).

Point Lookout Sandstone: The Point Lookout Sandstone was deposited in shallow water and along beaches in a regressing sea (figure 7). The light- gray to yellowish-gray vertical cliffs along the rim of Mesa Verde represent the massive upper sandstone member. The massive sandstone intertongues with the lower sandstone and shale member so the thickening of the beds is gradual. The Point Lookout Sandstone is 89- 115 m (291- 377 ft) thick. The formation was named for Point Lookout, but a type locality has yet to be designated.

For the amount of sand that was deposited , sedimentation rates must have been rapid or basin subsidence decreased, or both. Fossils in the sandstone are few because, as the sea withdrew, the water depths became shallower , the sediments coarser (sand sized), and the wave energy increased so that, like today, wave and current action destroyed whatever shells washed into the area. In addition, bottom- feeding scavengers worked through the sediments and further disintegrated any organic remains. Beach sands built upward and outward, forcing the sea to withdraw. As the sea withdrew, a broad, almost flat, coastal plain emerged from what used to be sea bottom. The sediments of the Menefee Formation were deposited on this coastal plain.

Menefee Formation: A lowland, coastal plain developed in the area as the sea retreated to the northeast (Cobban et al., 1994; Scott et al., 2001). Sediments deposited in swamps, lagoons, and along broad meandering streams became the woody shales, coal, dark carbonaceous shales, and discontinuous irregular sandstones of the Menefee Formation. Overall, the Menefee is a sedimentary wedge that thins to the northeast and thickens to about 244 m (800 ft) at the Colorado- New Mexico border.

In Mesa Verde National Park, 122 m (400 ft) of Menefee Formation was measured in a vertical section along the East Rim and provides a good idea of the heterogeneous mixture of sandstone, siltstone, shale, and coal in the unit (sections 34 and 35, Township 35 North, Range 14 West) (Wanek, 1959). The formation was named for Menefee Mountain in Montezuma County where coal is mined. Menefee Mountain has been referred to as the type locality; however, no type locality has been officially designated.

Within 16 m (53 ft) of the base of the Menefee, two beds of Point Lookout sandstone lie between the black to dark gray shale, shiny black coal, and yellowish- gray siltstone of the lower member (Wanek, 1959). The interfingering of Point Lookout sandstones with Menefee shales and siltstones near the base of the Menefee Formation suggests that the sea did not recede uniformly but in episodic pulses.

The bentonite beds deposited throughout the Menefee Formation suggest renewed volcanic activity and subsequent uplift from active plate convergence. In the middle member, an especially thick bentonite bed, as much as 1 m (3 ft) thick in some places, underlies a sandstone channel and represents deposition of a large amount of volcanic ash. Broken tree trunks, carried into the valley by mudflows, were deposited in some of these volcanic ash beds (Griffitts, 1990).

Vigorous volcanic activity in the Late Cretaceous resulted from thick accumulations of magma generated above the subduction zone on the western margin. Plutons were actively emplaced along the Sierra Nevada of California and Nevada as well as in southwestern Arizona at this time (Christiansen et al., 1994).

Cliff House Sandstone: The Cliff House Sandstone represents a shallow, near shore marine environment that covered the Mesa Verde area from about 75 to 79 Ma (figure 8). The shoreline trended in a northwest-southeast direction. The few preserved fossils suggest that the seawater was well circulated. Like today's beaches, the Mesa Verde area was probably rich with marine life that was not preserved. Winnowing and reworking by waves and currents sorted the sediment into sand size particles and destroyed much of the shell material. Scavengers on the surface and in the sediment further ravaged any organic remains, leaving little to be preserved as fossils.

The Cliff House Sandstone is named for the famous Ancestral Puebloan cliff dwellings. Currently, no type locality has been designated (http://ngmdb.usgs.gov/lex-bin). The thickness of the Cliff House is variable. In 1959, Wanek measured 86 m (281 ft) and 116 m (379 ft) of Cliff House in two vertical sections in the Wetherill Mesa area (sec.18- T34N- R15W) and recorded a maximum thickness of about 122 m (400 ft) in Echo Cliff. The original thickness of the Cliff House Sandstone is not known because an indeterminate amount of sand was removed by erosion. North of the park, near Cortez, the formation thins to approximately 41 m (134 ft) (Wanek, 1959).

Because of the complex interplay among chemical and mechanical weathering processes, groundwater flow, and groundwater sapping, the contact between shale zones and sandstone determine the location of the alcoves in the Cliff House, and consequently, the cliff dwellings (Harris et al., 1997). The upper sandstone unit becomes shaleier, thinner, and less resistant to erosion in the northern part of the park. Rather than forming prominent cliffs, the unit forms slope deposits.

Burrows left by the crustacean, *Ophiomorpha*, a shrimp-like organism, are indicative of a sandy environment where relatively high levels of wave energy have produced a clean, well- sorted, loose or shifting sandy substrate. These energy conditions commonly are found on the foreshore and shoreface of beaches, bars and spits (Pemberton, 1992). Sandstone troughs filled with *Inoceramus* (a clam) may represent tidal channels that breached barrier- island deposits (Aubrey, 1991). When the shoreline migrated to the northeast, swamps and coastal lagoons formed. Organic matter deposited in these anoxic environments became seams of coal.

In general, the Cliff House Sandstone represents deposition during a transgressive episode, but the history is far more complex than that. Few, if any, transgressive cycles have resulted in massive sandstone deposits over 122 m (400 ft) thick. Rather, the thick sandstone deposits probably were deposited when the sea level was static (Aubrey, 1991). At these times, the amount of sediment exceeded the rate of basin subsidence and piled up along the shore. If the rate of subsidence exceeded the rate of sedimentation, sea level rose rapidly without disturbing these deposits (Wanek, 1959). The interfingering sandstone, siltstone, shale, and coal beds indicate an overall episodic transgressive sequence punctuated with minor transgressions and regressions.

Although the Cliff House Sandstone is the top layer of rock seen at Mesa Verde today, it is not the end of the Mesozoic history of the Mesa Verde region. After deposition of the Cliff House Sandstone, sea level continued to rise, pushing the shoreline farther into northwestern New Mexico to the area of Chaco Cultural National Historical Park in Chaco Canyon. Offshore mud was deposited over Mesa Verde, and the sediments compacted into shale forming the Lewis Shale.

Then the sea began what was to be its final regression off the North American continent. As the sea receded, another beach deposit similar to the Point Lookout Formation was deposited over the area. This sandstone is known as the Pictured Cliffs Sandstone in the Four Corners region. Still more sandstone and shale of the continental and near- shore Fruitland and Kirkland formations were deposited as sea level continued to fall. These deposits, however, have been eroded from MEVE. In all, a total of about 457 m (1,500 ft) of latest Cretaceous sediments have been eroded from the Mesa.

Cretaceous – Tertiary Laramide Tectonics

The Laramide Orogeny (about 75- 35 Ma) transformed the extensive basin of the Cretaceous Interior Seaway into smaller interior basins bordered by high arches (anticlines and synclines on the scale of miles). The Laramide Orogeny developed when the North American plate collided with the Farallon plate. Although the collision took place far to the west, the tectonic stresses extended to the Colorado Plateau.

The Colorado Plateau, as a whole, was uplifted and tilted so that streams, flowing to the northwest, began to erode the underlying sedimentary rocks and to deposit gravels and sandstones across the area (Fassett, 1985; Aubrey, 1991). The relatively complete latest Cretaceous sedimentary record in the San Juan Basin indicates that basin formation was coincident with uplift. Deeply weathered, lateritic paleosols discovered just north of the Colorado Plateau in Tertiary- age deposits attest to a tropical climate (lateritic soils are common in tropical climates today) wherein the heat and abundant precipitation would have accelerated weathering and erosion processes on the broad uplifts (Chapin and Cather, 1983).

With continued uplift in the late Tertiary and Quaternary, the 457 m (1,500 ft) of Upper Cretaceous strata was eroded from the mesa to expose the Mesa Verde Group. At Mesa Verde, this unconformity at the Cretaceous – Tertiary contact can be observed at the east side of Moccasin Mesa (sec. 2- T33N- R15W) where Tertiary gravel deposits fill channels about 6 m (20 ft) deep carved into the underlying Upper Cretaceous, Cliff House Sandstone (Wanek, 1959).

Cenozoic Era: Tertiary Period and Uplift of the Colorado Plateau

Near the end of the Laramide Orogeny, from about 26- 35 million years ago, in early mid- Tertiary time, volcanic activity erupted across the Colorado Plateau. The laccoliths that formed the Sleeping Ute Mountain, La Plata Mountains, Henry Mountains, La Sal Mountains, and Abajo Mountains were emplaced during mid- Tertiary volcanism that also gave rise to the extensive San Juan volcanic field in southern Colorado, east of Mesa Verde National Park (Fillmore, 2000). A few northeast trending igneous dikes cut through Mesa Verde National Park and appear to be related to small igneous plugs in the region.

Today, Late Cretaceous shoreline deposits are found on the Colorado Plateau at elevations of several thousands of feet. Since the end of the Cretaceous Period 66 million years ago, the Colorado Plateau has risen about 3,660 m (12,000 ft) (Fillmore, 2000). Some of this uplift occurred quite rapidly in geologic time. As the rate of uplift increased, so did the rate of erosion. The Colorado River, for example, carved its present course within the last 6 million years.

On the mesa, remnants of gravel deposits ranging in thickness from a few feet to about 18 m (60 ft) overlie the erosional surface of the Cliff House Sandstone (Wanek, 1959). The deposits appear to be water laid and include polished pebbles and cobbles of jasper, quartzite, and igneous rocks similar in composition to the intrusive bodies in the La Plata Mountains to the northeast.

Cenozoic Era: Quaternary Period

Several small plugs and dikes of igneous rocks are intruded into the Cretaceous sedimentary rocks on the Mesa. The dikes show a northeastward trend and have been identified as minette, a basaltic rock that contains abundant biotite flakes and olivine crystals (Wanek, 1959). Several of these dikes appear to be similar in lithology and trend to the igneous dikes in the Shiprock area. The age of these intrusions is considered to be early mid- Tertiary (Wanek, 1959).

In the Pleistocene (0.01- 1.6 Ma) Ice Ages, streams carved deep valleys and river channels into the plain, isolating Mesa Verde as a gently sloping block in a broad valley. Gravel was deposited by meltwater flowing from glaciers in the high mountains. The 2- 3° tilt to the mesa caused streams to downcut their channels and dissect the mesa into parallel canyons. In the wetter climate, groundwater flow through the permeable Cliff House Sandstone was restricted at the contact with less permeable shale and siltstone layers. The groundwater flowed horizontally along the contact until it met the canyon walls and then seeped out onto the surface. Over time, deep alcoves began to form, primarily in the Cliff House Sandstone, as the porous sandstone was eroded. During interglacial periods, wind from the southwest brought silt onto Mesa Verde to develop into the rich, fertile soil that would later be exploited by the Ancestral Puebloans.

The Colorado Plateau as a whole has been subjected to repeated minor uplifts and stream rejuvenation since the end of the last ice age. Today, the climate is drier than during the Pleistocene Ice Ages yet the intermittent streams in the canyons are still in a period of active downcutting, only at a slower rate than in the past.

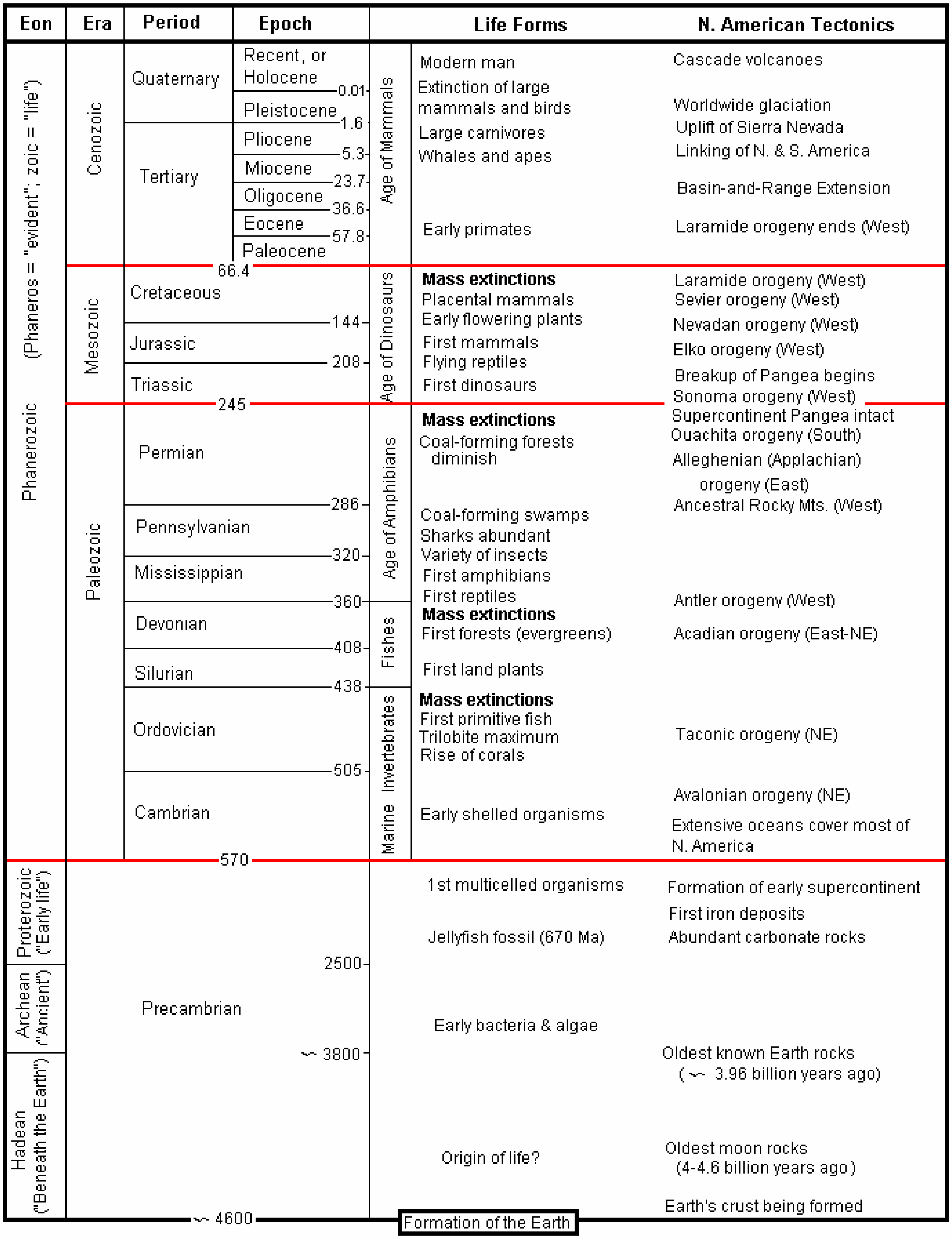

Figure 3. Geologic time scale. Red lines indicate major unconformities between eras. Absolute ages are in millions of years. From U.S.G.S.

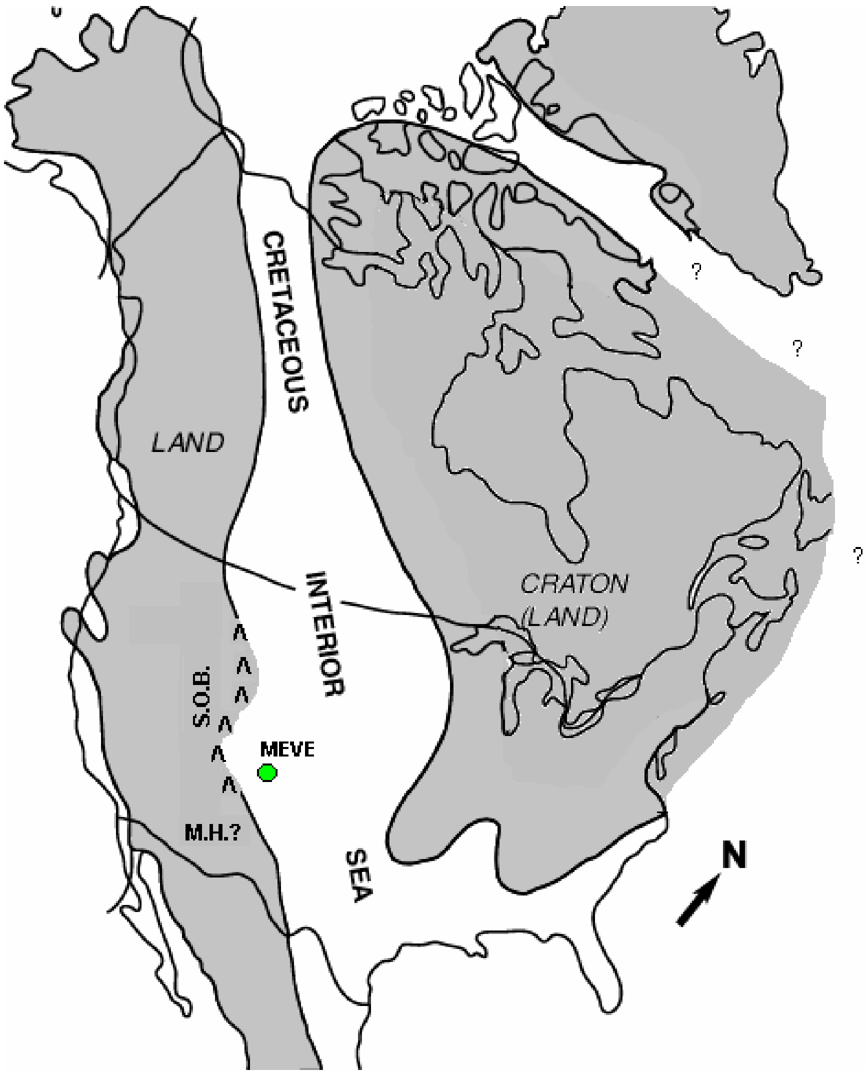

Figure 4. Location of the Cretaceous seaway. Shaded areas indicate land above sea level. MEVE: Mesa Verde National Park. SOB: Sevier Orogenic Belt. MH: Mogollon Highland that may have been present in southwestern Arizona. North arrow indicates the Cretaceous north. Modified from Rice and Shurr (1983).

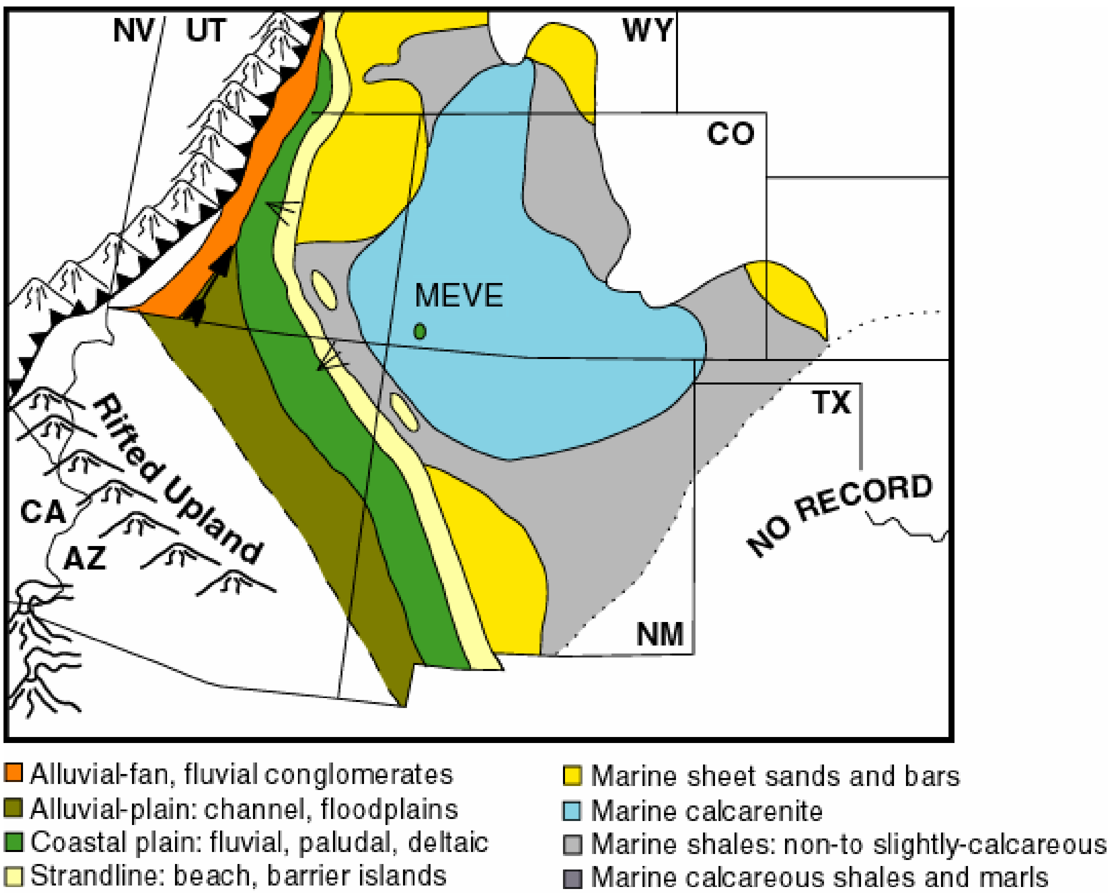

Figure 5. Paleogeographic map of Late Cretaceous, lower Mancos Shale environments during deposition of the Juana Lopez member. Large arrow indicates near shore sediment transport direction. Saw teeth mark the leading edge of thrust faulting with the teeth on the overriding plate. MEVE: Mesa Verde National Park. Modified from Elder and Kirkland (1994).

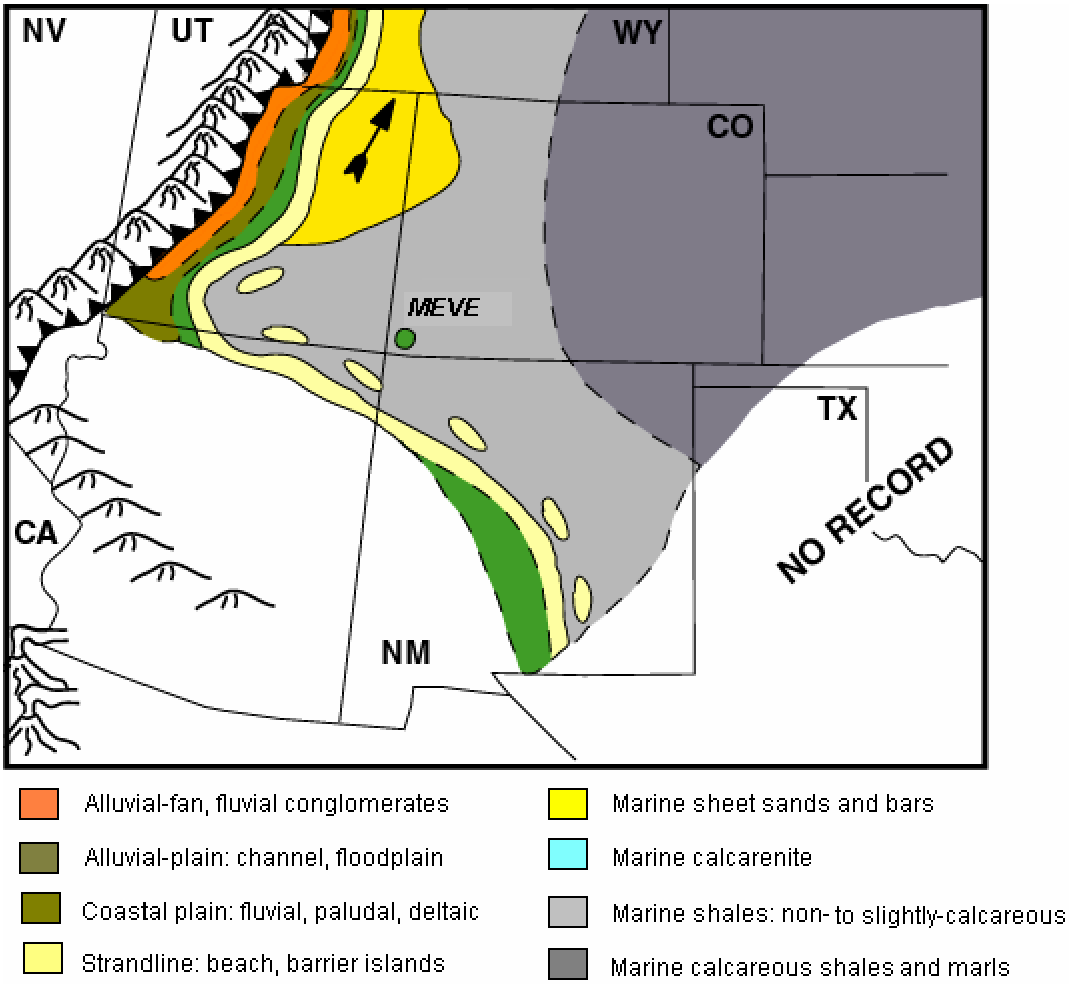

Figure 6. Paleogeographic map of Late Cretaceous, upper Mancos Shale environments during deposition of the Cortez member. Large arrow indicates near shore sediment transport direction. Saw teeth mark the leading edge of thrust faulting with the teeth on the overriding plate. MEVE: Mesa Verde National Park. Modified from Elder and Kirkland (1994).

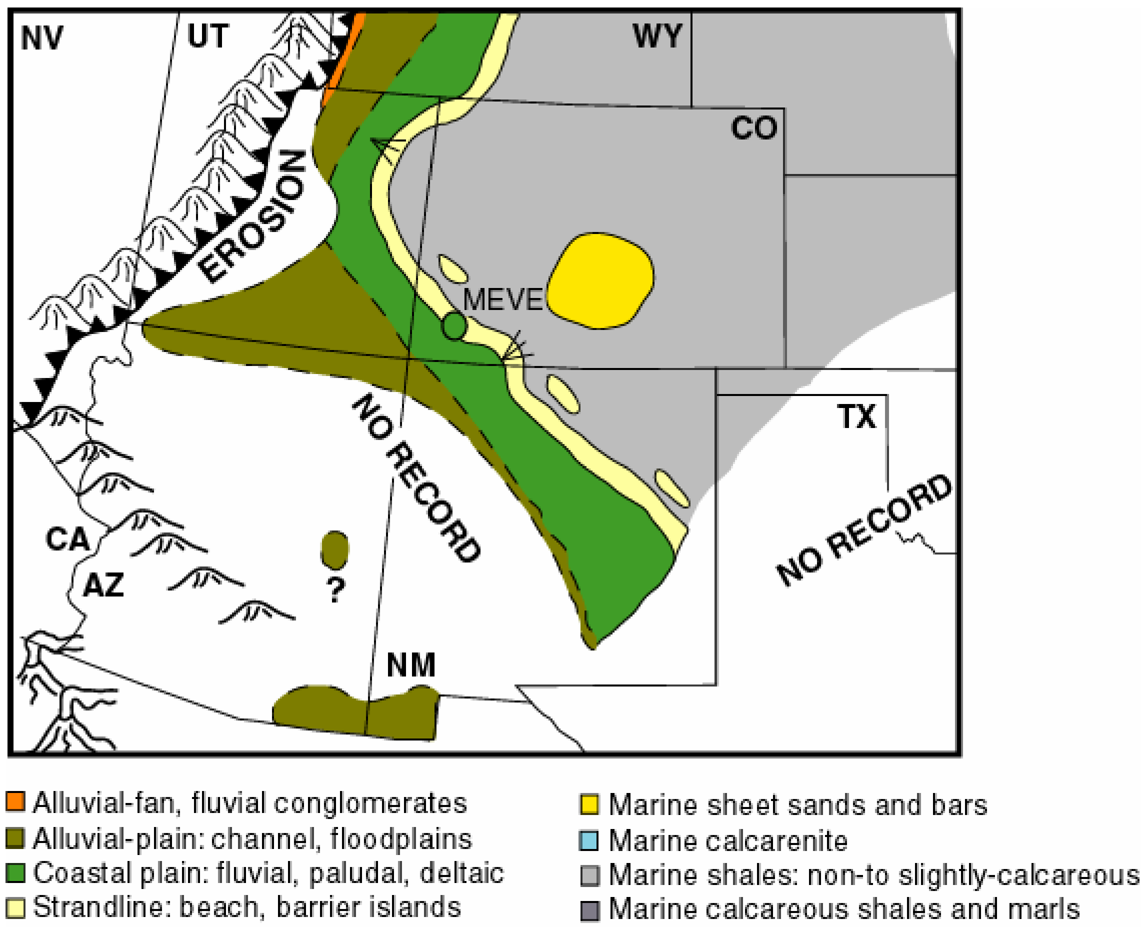

Figure 7. Paleogeographic map of environments present during Late Cretaceous, Point Lookout Sandstone time. Large arrow indicates near shore sediment transport direction. Saw teeth mark the leading edge of thrust faulting with the teeth on the overriding plate. MEVE: Mesa Verde National Park. Modified from Elder and Kirkland (1994).

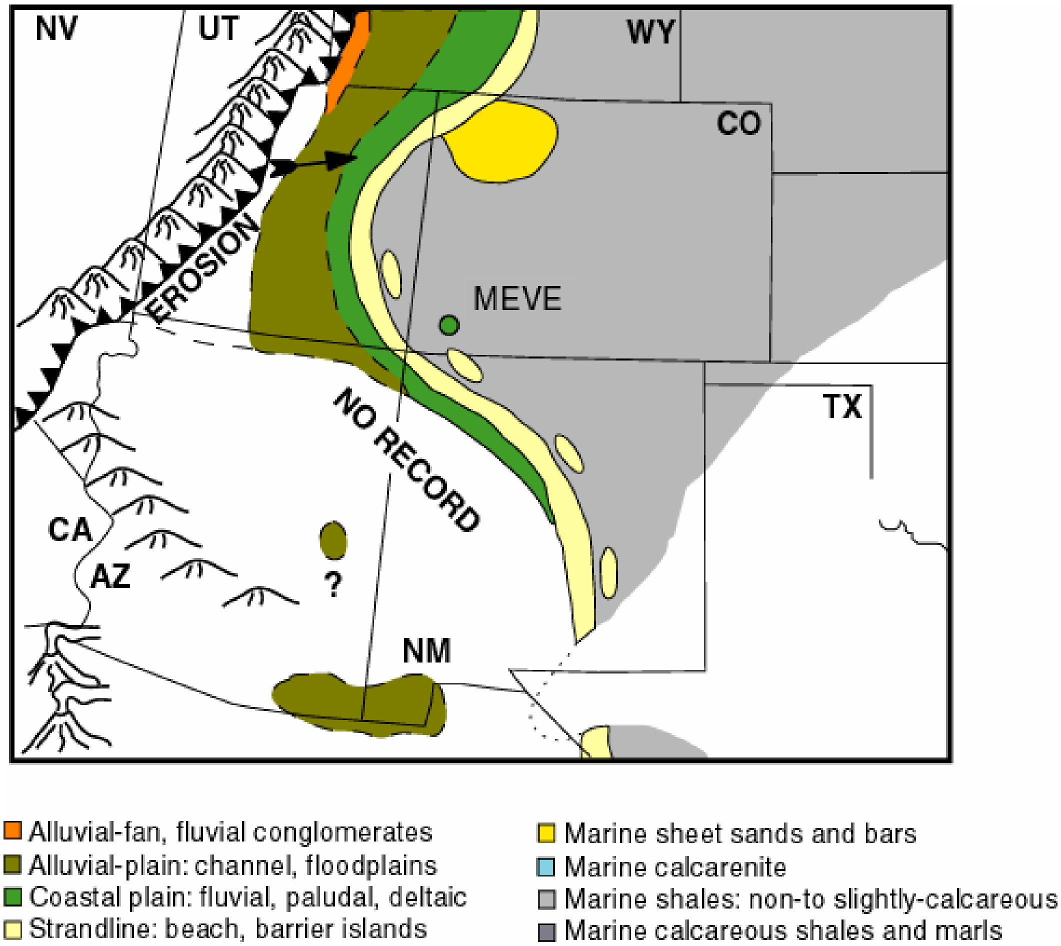

Figure 8. Paleogeographic map of depositional environments present during Late Cretaceous, Cliff House Sandstone time. Large arrow indicates near shore sediment transport direction. Saw teeth mark the leading edge of thrust faulting with the teeth on the overriding plate. MEVE: Mesa Verde National Park. Modified from Elder and Kirkland (1994).

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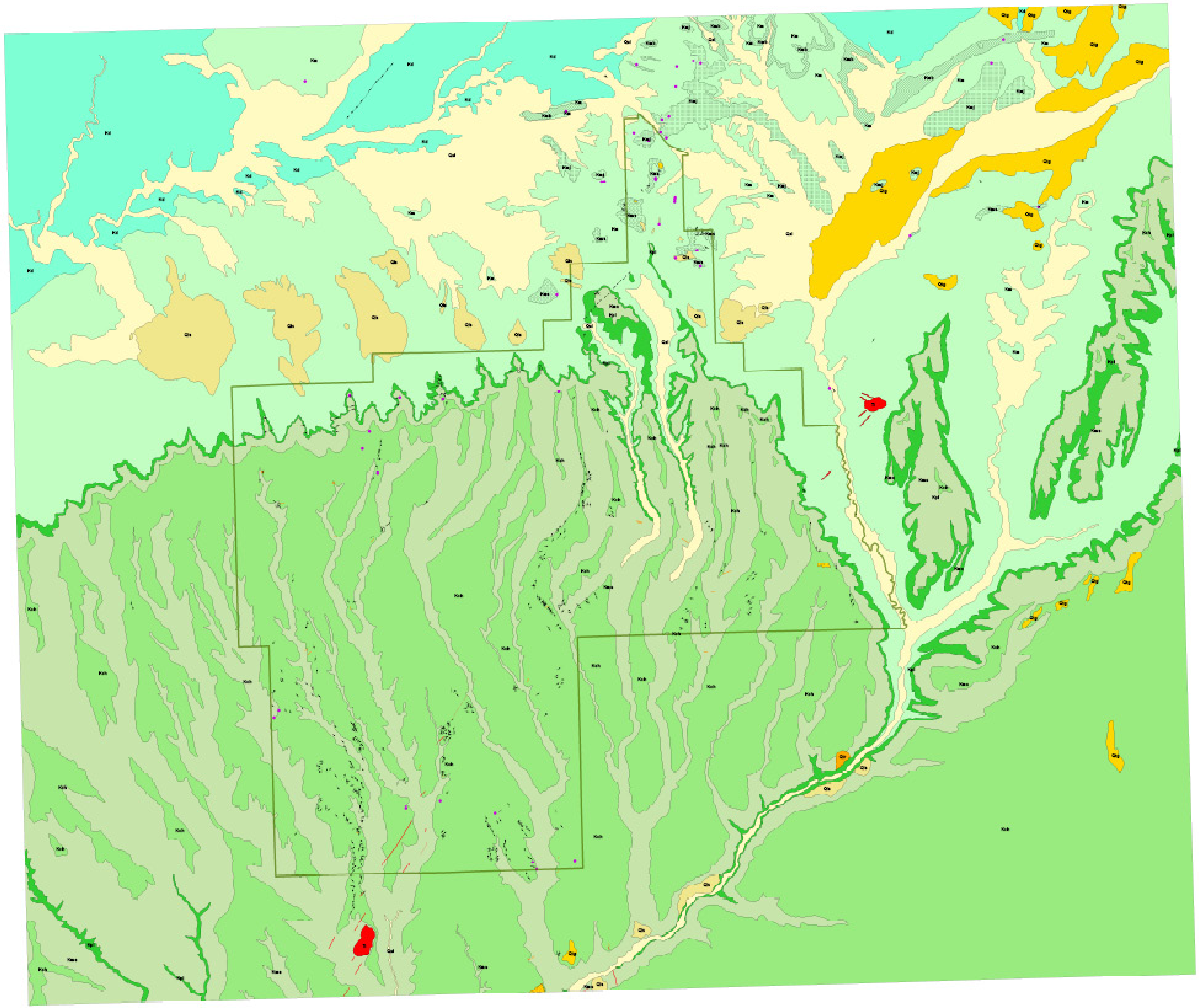
Appendix A: Geologic Map Graphic

The following page provides a preview or "snapshot" of the geologic map for Mesa Verde National Park. For a poster size PDF of this map or for digital geologic map data, please see the included CD or visit the GRE publications webpage: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

Geology of Mesa Verde NP



The original maps digitized by NPS staff to create this product were:

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Base maps from U.S. Geological Survey 7.5 minute series topographic quadrangle maps Cortez (1965, photorevised 1979), Point Lookout (1965, photorevised 1973), Mancos (1965), Wetherill Mesa (1966, photorevised 1975), Moccasin Mesa (1967, photorevised 1975), and Trail Canyon (1966), Colorado; also from 7.5 minute series orthophotoquads Cortez (1975), Point Lookout (1978), Mancos (1978), Wetherill Mesa (1975), Moccasin Mesa (1975), and Trail Canyon (1975), Colorado.

Digital geologic data and cross sections for Mesa Verde National Park, and all other digital geologic data prepared as part of the Geologic Resources Divisions Geologic Resource Evaluation program, are available online: http://www2.nature.nps.gov/geology/inventory/gre_publications.cfm

NPS Boundary

Geologic Attitude and Observation Points
- strike of vertical joints
- upthrown side of fault
- downthrown side of fault

Age Date Localities
- paleontologic sample

Linear Joints
- joint, known location

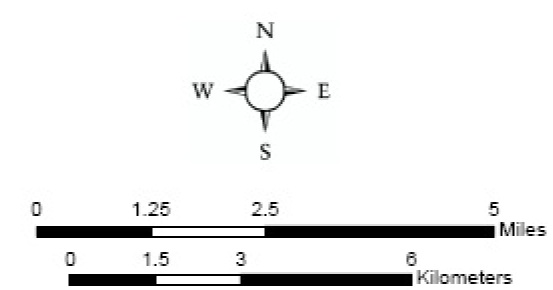
Faults
- approximate location
- inferred location

Linear Dike Units
- Ti - known location
- Ti - approximate location

Geologic Contacts
- known location
- approximate location
- concealed location
- quadrangle boundary

Linear Geologic Units
- Qtr - travertine

Geologic Units
- Qal - alluvium
- Qls - colluvium
- Qtg - high level terrace gravels
- Qtgt - high level terrace gravels with travertine cement
- Qtr - travertine
- Ti - minette
- Kch - Cliff House Formation
- Kme - Menefee Formation
- Kpl - Point Lookout Formation
- Km - Mancos Formation
- Kms - Mancos Formation, Smoky Hill oyster bench
- Kmj - Mancos Formation, Juana Lopez Member
- Kmb - Mancos Formation, Bridge Creek Member
- Kd - Dakota Sandstone



Appendix B: Scoping Summary

The following excerpts are from the GRE scoping summary for Mesa Verde National Park. The scoping meeting occurred on July 14- 15, 1998; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact to the Geologic Resources Division for current information.

Workshop Cooperators

Larry Wiese, MEVE Superintendent
George San Miguel, MEVE NE
Marilyn Colyer, MEVE NR
Allan Loy, MEVE GIS
Chris Wilkins, MEVE GIS
Will Morris, MEVE Interpretation
Gary Gasaway, MEVE Maintenance
Mary Griffitts, MEVE VIP Geologist
Mary Gillam, MEVE VIP Geologist/Consultant
Bruce Heise, NPS GRD
Tim Connors, NPS GRD
Joe Gregson, NPS NRID I&M
Jim Fassett, USGS Geologist
Doug Ramsey, NRCS Soil Survey
Chris Carroll, CGS Denver

Workshop Summary

An inventory workshop was held at Mesa Verde National Park on July 14- 15, 1998 to discuss the park's geologic resources and associated issues and needs. Mesa Verde N.P. also administers Yucca House National Monument and the easternmost unit of Hovenweep National Monument, Goodman Point. Fourteen cooperators participated in the one and a half day workshop.

Larry Wiese, MEVE Superintendent, attended the first part of the meeting and noted in his remarks that MEVE is a World Heritage Site. After introductions by the participants, Joe Gregson presented an overview of the NPS I&M Program, the status of the natural resource inventories, and the Geological Resources Inventory (GRI). Bruce Heise followed with an overview of the organization of the Natural Resource Stewardship and Science Washington Office, GRD, and the Colorado pilot project. Afterward, Marilyn Colyer and Alan Loy facilitated and compiled a flip chart of geologic hazards and needs.

Hazards

Hazards were discussed at length. In general, the types of hazards at Mesa Verde may be divided into geologic hazards and land use hazards. Land use hazards include slumping and rock falls associated with roads, location of septic systems, utilities, and building sites, as well as damage to archeological features. Geologic hazards in general include rockfall, debris flows, landslides, slumps, flood erosion and deposition, and swelling soils.

Although rock falls are probably the #1 hazard to the public in the park, especially along roads and trails (e.g., the Boulder Nest section of the entrance road), little can be done at present other than the ongoing road hazard monitoring and cleanup.

Major slumps and landslides have affected park roads several times through the years. The group knew of only one M.S. thesis that had studied the road landslides (Dan Plasea, date?). Several slump- prone areas have been repaired and engineered to limit the local water infiltration rate and/or to drain and reduce pore-pressure in the affected sediment, but new areas of concern appear each year. Since the park has only one major road, a major slump or washout has the potential to trap a considerable number of visitors in the park. None of the group knew if an emergency plan existed to address a major road failure, so the park staff volunteered to check (as of this report, no new information had been forthcoming – ed.).

Recent episodes of water seeping into alcoves and causing archeological damage or back (roof) collapse were discussed. Some of the seepage was traced to the drainage of domestic water and septic system leaching and subsequently mitigated. The need for better understanding of local groundwater systems, recharge areas, and infiltration/conductivity rates was outlined. Although Resource Management Plan project statements have been written to study the local groundwater and spring locations, as yet, none have been funded. The locations of springs have archeological significance as sites of alcove development and relate directly to the paleo- demography of the ancient inhabitants. Win Wright, a local groundwater consultant, has done some work in the park and may be approached about a potential groundwater project or report.

Routing of a new pipeline for the park's domestic water was discussed. Mary Griffitts expressed reservations about the fact that the water line will be placed in a slant-drilled hole that crosses a major joint system that might be prone to faulting, especially if the water line ruptured. The drilling process and use of lost circulation materials for drilling in areas such as this were briefly discussed.

Flood hazards and erosion in burned areas of the park have increased since the major fires in the recent past. Increased runoff from the burned areas contribute to increased flooding (minor as yet), and a hydrologic study of these areas would help answer management questions related to potential flood magnitude. Especially important is the need to delineate floodplains for land use and construction plans.

Debris flows also present human hazards that are relatively low right now but will probably gain importance as outside development encroaches on the park's boundary. Mesa Verde is a highland with ephemeral canyons, subject to debris flows, draining outward onto adjacent lands. Mary Gillam stated that the terraces and benches in the Mancos Valley were covered with debris flow sediments. Locations in and near the mouths of Mesa Verde's ephemeral canyons are in highly- hazardous debris flow areas, which should be considered in land use planning.

Research Needs

Geologic research is needed and should be encouraged—both in the Cretaceous Mesa Verde Group rocks and in the Quaternary and other deposits.

In the Cretaceous rocks, the depositional history of the Cliff House Sandstone, which has its best exposures in the park, records an extensive transgressive phase of the Mancos Sea. Furthermore, the sequence stratigraphy of the Mesa Verde type section has never been studies in detail, and the type section itself has never been defined. Mary Griffitts suggested that extensive work on the Cretaceous fossil record, especially plants, is needed to enhance correlation and dating of the rocks, especially the Menefee Sandstone. A comparative collection and terminology for Cretaceous fossils is also needed.

Numerous igneous dikes cut the Cretaceous sedimentary rocks of Mesa Verde, and a study of their areal extent and petrography would greatly enhance the understanding of their origin and emplacement.

There was discussion of the discovery and radiometric dating of charcoal in sediments at Colorado National Monument (COLM) and its implication for potential fire recurrence studies. Although this had never been considered at MEVE, the recent fire and changes in runoff suggest the need to review and evaluate the potential for gleaning fire history from Quaternary deposits. The NPS fire program will visit COLM in October to evaluate these ideas. Bruce Heise will participate and report on the potential for further study.

The NRCS has recently completed fieldwork for a soil survey of the park as part of the Montezuma County project. Doug Ramsey said that the digital map should be ready by early next year and will be forwarded to the park and the I&M Program (as of 2003, neither the digital map nor the soil report has been received by I&M cooperators compiling this report – ed.).

Additional studies of the Quaternary deposits are needed. Paleosols contain information on previous climatic conditions in the area. As noted in the hazards section, locations of rockfall, debris flow, landslide, slump, colluvial, and alluvial deposits are important to know for land use considerations. A detailed surficial geology map is a high priority for the park and would provide insight for both modern land use as well as ancient land use related to the cultural resources.

Interpretation

Interpretive needs and current resources were discussed. Mary Griffitts has written a generalized book, *Guide to the Geology of Mesa Verde National Park* that is sold in the museum and visitor center. Other saleable items are needed and might include a fire history, a detailed geologic map, a geologic road log, and the inventory report. A road log/guide for the Colorado Plateau region would provide a connection for visitors traveling from park to park. Documentation and illustration of geologic units exposed in several parks would make a good common theme that could include correlated cross sections between associated parks. Road log/guides from Mesa Verde to adjacent parks would also provide continuity between units. Most of the items for visitor sale should be written in lay terms. MEVE staff also pointed out that the fire had burned out some existing exhibits and signs that have not yet been replaced. Road signs for geologic unit names and unique features were suggested and discussed, but new signs might not be approved due to both traffic safety and flow issues. A suggestion that road sign text be kept short and simple with visitors using a more detailed guidebook explaining the features seemed to be a more workable and acceptable alternative.

Maps

Maps were discussed at length and considered by the group to be one of the more valuable products that the geologic inventory could provide.

A 1:50,000 scale geologic hazard map exists for La Plata County but there is no hazard map for Montezuma County or MEVE available. As discussed earlier, a geologic hazards map or set of GIS layers are needed for the park.

A surficial geologic map of Mesa Verde is also not available. Although a surficial map would require a new mapping project, it would be valuable for land use planning, cultural resource demographic studies, and geologic hazards assessment.

The existing geologic map for MEVE is on a planimetric base (USGS Bull. 1072- M, Plate 49, or USGS Geologic Map OM- 152, Wanek, 1959) that is not tied to the topography (i.e., significant location errors probably exist). In addition, other smaller scale geologic maps cover MEVE but are not suitable for digitizing. Fortunately, Mary Griffitts has just completed mapping the geology and faunal zones of the park on a topographic base that can be combined and compiled into a suitable map for the digital geology (as of 2003, this map has not surfaced,). Jim Fassett offered to map the missing coal seams and add them to the project at minimal cost. Alan Loy will work with Mary and Jim to get the maps digitized once compiled. Alan will also work with Joe Gregson to coordinate the GIS attributes and resulting map products. Once the map is complete, the park Team will consider publication of the map in coordination with the park's natural history association.

GIS layers and geologic attributes for the GIS data that were discussed include:

- lithology (formations, members(?), and faunal zones in the Mancos Shale)
- joints and faults
- travertine
- unique features (T&E species related to specific rocks and the erosional sun symbols in the Cliff House Sandstone)
- springs and alcoves
- intrusives
- silcretes, ash beds, and gravels

Mary Griffitts will also provide geologic maps for Yucca House N.M. and the Goodman Point unit of Hovenweep N.M. for digitizing into the GIS (the remainder of HOVE is administered by the SE Utah Group and will be evaluated separately) (as of 2003, Griffitts has provided neither of these maps). Yucca House N.M. has gravels, Mancos, and Juana Lopez (?) exposed. Goodman Point is thought to be all in the Dakota Sandstone.

A soils map is needed, but the recently completed survey by NRCS should satisfy this need for both the park and the NPS I&M Program soils inventory (contact Pete Bigham, GRD, for further information).

Report

Several of the cooperators were willing to work on and complete a geologic report for the park within about a year. At first, Bruce Heise was chosen as compiler and editor, but Jim Fassett will assume that role as a condition of his involvement by the USGS. The report will be peer reviewed and published as a USGS Professional Paper or Bulletin. Mary Griffitts will be the senior author with other contributions coming from Jim (regional and coal geology), Mary Gillam (Quaternary geology), Doug Ramsey (soils), Alan Loy (map preparation), and hopefully, a section on the
8.
groundwater/springs by Win Wright, Bob Jarrett, or Larry Martin (as of 2003, no report has been forthcoming from these authors, thus, the need for this GRE report – ed.)

Action Items

1. Mary Griffitts has recently completed mapping the park on 1:24,000 scale topographic base maps which she and park staff will compile into a geologic master on a stable mylar base.
2. Jim Fassett volunteered to map the missing coal seams and add them to the map. Jim thought that this project would take 2- 4 weeks and could be done for the cost of his travel to the park (the park would provide housing and with I&M funds for transportation and per diem).
3. Once the mylar master is ready, Alan Loy, the GIS Specialist at the park, will digitize the maps with the assistance of Mary Griffitts (geology) and Joe Gregson (GIS model).
4. Jim Fassett, Mary Griffitts, and Mary Gillam agreed to co- author a geologic report for the park that will be used for sections of the I&M report. A USGS Bulletin or Professional Paper would require that Jim be the scientific editor and that the report be peer reviewed. Completion of the report should take about one year (as of 2003, the Griffitts/Gillam report has not been completed, thus, the need for this GRE report – ed.).
5. Joe Gregson will seek permission from the Mesa Verde National Park Natural History Association (MVNPNHA) to publish Mary Griffitts' existing report and map in the I&M Program's Internet database.
6. Publication plans for the final Mesa Verde National Park geologic map will be reviewed upon completion and in cooperation with the USGS and MVNPNHA as needed.
7. GRD and the MEVE Park Team will assist with preparation of mapping proposals and RMP project statements to complete surficial geology and geologic hazards for the park.

Mesa Verde National Park

Geologic Resource Evaluation Report
NPS D-270, March 2006

National Park Service

Director • Fran P. Mainella

Natural Resource Stewardship and Science

Associate Director • Michael A. Soukup

Natural Resource Program Center

The Natural Resource Program Center consists of six divisions: Air Resources, Biological Resource Management, Environmental Quality, Geologic Resources, Natural Resource Information, and Water Resources Divisions. The Geologic Resources Division, in partnership with parks and others, works to protect, preserve, and understand the geologic resources of the National Park System and to protect park resources from the adverse affects of mineral development in and adjacent to parks. One of the functions of the Division, carried out in the Planning Evaluation and Permits Branch is the Geologic Resource Evaluation Program. This program develops digitized geologic maps, reports, and bibliographies for parks.

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Production of this geologic report was facilitated by the NPS Colorado Plateau Cooperative Ecosystem Studies Unit.

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